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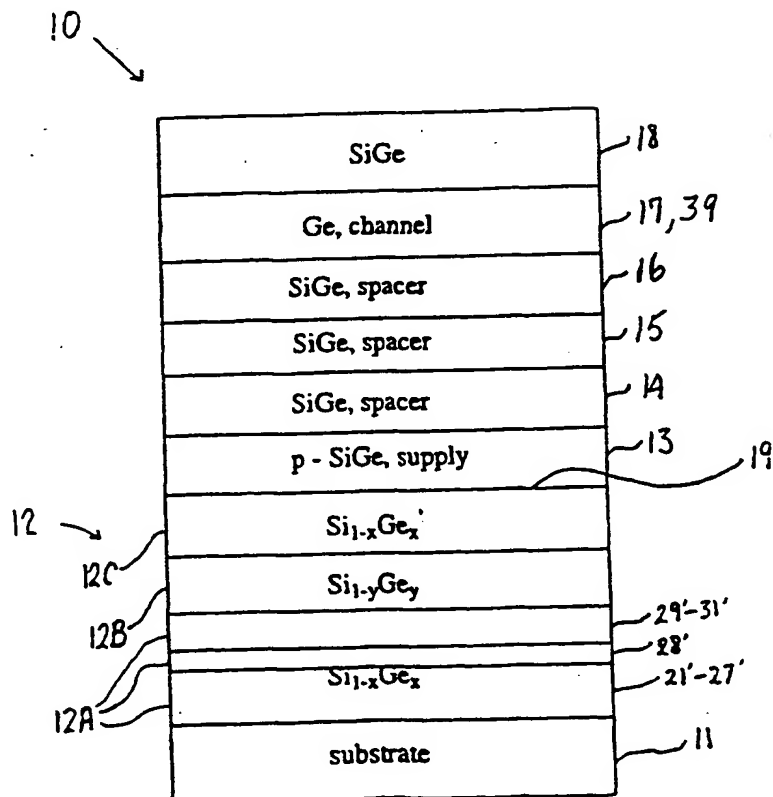
## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(54) Title: **HIGH SPEED GE CHANNEL HETEROSTRUCTURES FOR FIELD EFFECT DEVICES**

## (57) Abstract

A method and a layered heterostructure for forming high mobility Ge channel field effect transistors is described incorporating a plurality of semiconductor layers on a semiconductor substrate, and a channel structure of a compressively strained epitaxial Ge layer having a higher barrier or a deeper confining quantum well and having extremely high hole mobility for complementary MODFETs and MOSFETs. The invention overcomes the problem of a limited hole mobility due to alloy scattering for a p-channel device with only a single compressively strained SiGe channel layer. This invention further provides improvements in mobility and transconductance over deep submicron state-of-the-art Si pMOSFETs in addition to having a broad temperature operation regime from above room temperature (425 K) down to cryogenic low temperatures (0.4 K) where at low temperatures even high device performances are achievable.



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**High Speed Ge Channel**  
**Heterostructures For Field Effect Devices**

**CROSS REFERENCE TO RELATED APPLICATION**

This application is cross referenced to Serial No. 09/267,323 filed March 12, 1999 by Jack O. Chu et al. entitled "High Speed Composite p-channel Si/SiGe Heterostructure for Field Effect Devices" which describes a field effect transistor with a channel having a composite layer of a layer of Ge and a layer of SiGe both under compression to obtain higher mobility which is incorporated herein by reference.

**Field of the Invention**

This invention relates to a silicon and silicon germanium based materials system and more specifically, to a novel epitaxial field effect transistor structure useful for high-speed low-noise, microwave, submillimeter-wave and millimeter-wave applications. Preferably, the epitaxial field effect transistor structure includes a high performance Ge channel in a structure incorporating silicon and silicon germanium layers to form CMOS devices or circuits, high electron mobility transistors (HEMT's), and modulation-doped heterostructure field effect transistors. This invention provides improvements in mobility and transconductance over deep submicron (0.1  $\mu\text{m}$  channel length) state-of-the-art Si pMOSFETs by using an extremely high mobility Ge channel device which can be advantageously operated in a broad temperature regime from above room temperature (373 K) to cryogenic temperatures (0.4 K) where even higher device performances are achievable.

### **Background of the Invention**

In high speed and low noise device applications, the focus has been on designing and fabricating high electron mobility transistors (HEMTs) or modulation-doped field effect transistors (MODFETs) where carrier (eg. electrons, holes) conduction occurs in an undoped channel layer such that the carrier mobility is not limited by impurity scattering and high carrier mobility is achieved. In general, these high speed electronic devices are often used as low-noise amplifiers, power amplifiers, satellite receivers and transmitters operating in the microwave and rf regime, and the material of choice is usually the faster but more expensive III-V materials system and technology such as GaAs and InP. A complicated and costly III-V materials technology is not very desirable in the semiconductor industry whereas a less-expensive SiGe materials system which is fully compatible with present Si technology is more desirable and far easier to integrate with existing Si-CMOS device technology.

One example of a material system compatible with Si technology is described in U.S. Pat. No. 5,019,882 which issued on May 28, 1991 to P.M. Solomon entitled "Germanium Channel Silicon MOSFET" and assigned to the assignee herein. In U.S. Pat. No. 5,019,882, a channel having improved carrier mobility comprises an alloy layer of silicon and germanium which is grown above a silicon substrate. The alloy layer is kept thin enough for proper pseudomorphic dislocation free growth to occur. A layer of silicon is formed over the alloy layer and is oxidized partially through to form a dielectric layer. A gate region is formed over the silicon dioxide.

A second example of a high performance SiGe device structure compatible with Si technology, is described in U.S. Pat. No. 5,534,713 which issued on July 9, 1996 to K.E. Ismail entitled "Complementary Metal-Oxide Semiconductor Transistor Logic Using Strained Si/SiGe Heterostructure Layers" and assigned to the assignee herein. In U.S. Pat. No. 5,534,713 a silicon

CMOS transistor structure is described utilizing a buried SiGe channel under compressive strain with enhanced hole mobility for a p-channel device, and a buried Si channel under tensile strain with enhanced electron mobility for an n-channel device fabricated on a strained Si/SiGe heterostructure design. Further in US 5,534,713 the proposed compressively-strained SiGe layer serving as a p-channel for the p-channel field effect transistor is described as having a composition of germanium in the range from 50 to 100% and with a preferred composition of 80%. Thus far, prototype SiGe p-channel MODFETs utilizing this channel design and composition at the Thomas J Research Center, IBM Corporation have yielded hole mobilities only up to 1,000 cm<sup>2</sup>/Vs at room temperature.

The compatibility and fabrication of a Ge-channel MODFET using existing Si technology has been demonstrated by molecular beam epitaxy (MBE) techniques where modulation-doped FET structures with hole channels consisting of a pure Ge layer were grown by molecular beam epitaxy on a Si substrate. In particular, room temperature hole mobility for a two-dimensional hole gas (2DHG) in a modulation-doped, strained Ge layer (grown by MBE) has been reported as high as 1,870 cm<sup>2</sup>/Vs in a publication by G. Höck, T. Hackbarth, U. Erben, E. Kohn and U. König entitled "High performance 0.25μm p-type Ge/SiGe MODFETs", Electron. Lett. 34 (19), 17 Sept. 1998, pp 1888-1889 which is incorporated herein by reference. In G. Höck et al., for the 0.25μm gate length devices, the p-type Ge channel MODFETs exhibited a maximum DC extrinsic transconductances of 160 mS/mm while the maximum drain saturation current reached up to a high value of 300mA/mm. For the RF performance, a unity current gain cutoff frequency  $f_T$  of 32 GHz and a maximum frequency oscillation  $f_{max}$  of 85 GHz were obtained.

There is a growing interest in designing and fabricating high speed low temperature MOSFETs and bipolar transistors for high speed cryogenic applications such as read out electronics for

cooled infrared detectors, fast processors, and low noise amplifiers. To this end, a Ge channel device structure which can be operated in the temperature range from room temperature (300 K) down to cryogenic temperature ( $T = 77$  K) while having even higher transport characteristic is the ideal solution. An example of a modulation-doped SiGe/Ge heterostructures with a 2D hole channel consisting of pure Ge which is operable at both room temperature and at 77 K has been reported in a publication by "U. König and F. Schaffler entitled "p-Type Ge-Channel MODFET's with High Transconductance Grown on Si Substrates", Electron. Dev. Lett. 14 (4), 4 Apr. 1993, pp 205-207 which is incorporated herein by reference.

Another example of a field effect transistor having a high carrier mobility suitable for high speed and low temperature operation is described in U.S. Pat. No. 5,241,197 which issued on Aug. 31, 1993 to E. Murakami et al entitled "Transistor Provided with Strained Germanium Layer". In U.S. Pat. No. 5,241,197, a strain control layer grown by molecular beam epitaxy is provided beneath a germanium layer to impose a compressive strain on the germanium layer. The composition of the strain control layer is used to generate the compressive strain. The carrier mobility in the strained germanium layer is reported to be  $3000 \text{ cm}^2/\text{Vs}$ . However, no measurements or data have been subsequently published of Ge properties or Ge layered structures with mobilities over  $2000 \text{ cm}^2/\text{Vs}$  at room temperature. Reported values of hole mobilities of Ge layered structures at room temperature of  $1900 \text{ cm}^2/\text{Vs}$  are found on page 315 and specifically in Table 8.1 of D.W. Greve, Field Effect Devices and Applications published in 1998 by Prentice-Hall, Inc. Upper Saddle River, NJ.

### Summary of the Invention

In accordance with the present invention, a silicon and silicon germanium based epitaxial structure for a p-type field-effect transistor that utilizes a single layer of Ge in a p-channel region is described for forming a p-channel device comprising a semiconductor substrate, a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the substrate where the Ge fraction  $x$  is in the range from 0.5 to 0.8, a second layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the first layer, a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the second layer, a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the third layer, a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the fourth layer, the third through fifth layers having a progressively lower value of  $x$  and a lower value of residual background concentration of p dopant, a sixth layer of undoped Ge formed epitaxially on the fifth layer whereby the Ge layer is under compressive strain and remains commensurate with respect to the first relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, and a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the sixth layer. A metal layer may be formed and patterned over the seventh layer to form the gate of the p-channel field effect transistors while the drain and source regions may be formed by forming p regions on either side of the gate in the layered structure. This layered structure design forms a modulation-doped heterostructure whereby the supply layer or the second p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer is located below the active Ge channel, the sixth layer. Furthermore, in this layered device structure, the spacer layer which separates the active channel from the supply layer employs a triple layer design comprising the third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$ , the fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$ , and a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  of progressively a lower value of  $x$  and a lower value of residual background concentration of p-type dopant. The progressively lower background dopant can be obtained by forming undoped  $\text{Si}_{1-x}\text{Ge}_x$  at a progressively lower temperature.

The invention further provides a method and a p-channel field effect transistor having extremely high hole mobility in its channel comprising a semiconductor substrate, a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the substrate where  $x$  is in the range from 0.5 to 0.8; a second layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the first layer, a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the second layer, a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the third layer, the third and fourth layers having a progressively lower value of  $x$  and a lower value of residual background concentration of p-type dopant, a fifth layer of undoped Ge formed epitaxially on the fourth layer whereby the Ge layer is commensurate with respect to the first relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, and a sixth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the fifth layer. This layered structure design describes a modulation-doped heterostructure whereby the supply layer or the p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer of layer 2 is separated from the active p-channel of the fifth layer by a double layer spacer design of the third and fourth  $\text{Si}_{1-x}\text{Ge}_x$  layers.

The invention further provides a method and a p-channel field effect transistor having extremely high hole mobility in its channel comprising a semiconductor substrate, a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the substrate where  $x$  is in the range from 0.5 to 0.8, a second layer of undoped Ge formed epitaxially on the first layer whereby the Ge layer is commensurate with respect to the first relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the second layer, a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the third layer, a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the fourth layer, and a sixth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the fifth layer. This layered structure design describes a modulation-doped heterostructure whereby the supply layer or the sixth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer is located above the active Ge channel of layer 2. Likewise, the supply layer or the p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer of layer 6 can be further separated above the active Ge channel of the second layer with the



addition of a strained Si spacer layer between the fifth layer and sixth layer, or alternatively between the fourth layer and fifth layer.

The invention further provides a method and a p-channel field effect transistor having extremely high hole mobility in its channel comprising a semiconductor substrate, a first layer having an upper surface of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the substrate where  $x$  is in the range from 0.5 to 0.8, a second layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the first layer, a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the second layer, a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the third layer, a fifth layer of undoped Ge formed epitaxially on the fourth layer whereby the Ge layer is commensurate with respect to the upper surface of the first relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a sixth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the fifth layer, a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the sixth layer, and an eighth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the seventh layer. This layered structure design describes a modulation-doped heterostructure whereby the active channel is symmetrically doped by two supply layers of the second and eighth layers located above and below the fifth channel layer and equally separated by a dual layer spacer design of the sixth and seventh layers above the channel, and the third and fourth layers below the channel respectively.

The invention further provides a method and a p-channel field effect transistor having extremely high hole mobility in its channel comprising a semiconductor substrate, a first layer having an upper surface of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the substrate where  $x$  is in the range from 0.5 to 0.8, a second layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the first layer, a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the second layer, a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the third layer, a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on

the fourth layer, a sixth layer of undoped Ge formed epitaxially on the fifth layer whereby the Ge layer is commensurate with respect to the upper surface of the first relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the sixth layer, an eighth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the seventh layer, and a ninth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the eighth layer. This layered structure design describes a modulation-doped heterostructure whereby the active channel is asymmetrically doped by two supply layers of 2 and 9 located above and below the channel layer 5 and unequally separated by a dual layer spacer design of the seventh and eighth layers above the channel, and a triple layer spacer design of the fifth, fourth and third layers below the channel respectively. Likewise, the asymmetrically doping can be accomplish by the reversed spacer layer design whereby the top supply layer is separated by a triple layer design above the channel while the bottom supply layer is separated by a dual layer spacer design below the channel.

The invention further provides a method and a complementary field effect transistor having extremely high hole mobility in its channel comprising a semiconductor substrate, a first layer having an upper surface of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the substrate where  $x$  is in the range from 0.5 to 0.8, a second layer of undoped Ge formed epitaxially on the first layer whereby the Ge layer is commensurate with respect to the upper surface of the first relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer, a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on the second layer, and a fourth layer of gate dielectric formed over the third layer. A doped polysilicon layer may be formed and patterned over the fourth layer to form the gate electrode of the field effect transistor while the source and drain regions may be formed by implanting either self aligned p-type or n-type regions on either side of the gate electrode in the layered structure. This layered structure design describes the

formation of a near surface Ge channel with high mobilities suitable for complementary (CMOS) field effect transistors for operation in the enhancement mode.

The invention further provides a method and a structure for a relaxed ( $>90\%$ )  $\text{Si}_{1-x}\text{Ge}_x$  buffer layer comprising a semiconductor substrate, a first layer of partially relaxed ( $<50\%$ )  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially by stepwise grading (or linear grading) where the Ge content of the layers is increased in a stepwise fashion (or a linear fashion) on the substrate and  $x$  is in the range from about 0.1 to about 0.9, a second layer of  $\text{Si}_{1-y}\text{Ge}_y$  formed epitaxially on the first layer where  $y = x + z$  and  $z$  is in the range of 0.01 to 0.1 which serves to "over relax" the layer to greater than  $x$ , and a third layer of  $\text{Si}_{1-n}\text{Ge}_n$  formed epitaxially on the second layer whereby the  $\text{Si}_{1-x}\text{Ge}_x$  layer is now more relaxed as compared to the original, partially relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer one. The extent of additional relaxation due to this "over shoot" layer of  $\text{Si}_{1-y}\text{Ge}_y$  does depend on the thickness of this layer which in turn would be limited by its critical thickness on the initial partially relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer. In the case when  $x$  is greater than 0.5 a double "over shoot" effect is preferred whereby the first "over shoot" is a  $\text{Si}_{1-m}\text{Ge}_m$  layer where  $m = 0.5x$ , and the second "over shoot" is a  $\text{Si}_{1-n}\text{Ge}_n$  layer where  $n = x + z$  and  $z$  is in the range of 0.01 to 0.1.

It is an object of the invention to provide a layered structure which allows for p-channel field effect transistors to be formed having a channel with extremely high hole mobility.

It is a further object of the invention to provide a p-channel device where the active channel is a strained Ge layer.

It is a further object of the invention to provide p-channel devices where the channel structure takes advantage of the higher compressive strain with the benefits of a higher barrier or a deeper confining channel for hole carriers as compared to a replacement channel using a single SiGe layer.

It is a further object of the invention to provide a buried channel of a Ge layer under compressive strain for a p-channel device.

It is a further object of the invention to provide a hole mobility of greater than  $1,000 \text{ cm}^2/\text{Vs}$  in an optimum p-channel structure composed of a strained Ge layer of 100-200Å thick to produce the highest hole mobility in the SiGe materials system.

It is a further object of the invention to provide a p-channel device where the spacer layer is a triple or dual layer design composed of either three or two SiGe layers respectively.

It is a further object of the invention to provide a p-channel device where the active channel is symmetrically doped by two supply layers located above and below the channel with a symmetrical dual spacer layer design.

It is a further object of the invention to provide a p-channel device where the active channel is asymmetrically doped by two supply layers located above and below the channel with an asymmetrical spacer layer design.

It is a further object of the invention to provide a near surface channel device where the active Ge channel has high electron and hole mobilities and may be operated in the enhancement mode.

It is a further object of the invention to provide a near surface channel device where the active Ge channel is suitable for making complementary MOSFET devices having high mobilities.

It is a further object of the invention to provide a layered structure and scheme where a desired relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer can be better achieved by the addition of a single over shoot layer (when  $x \leq 0.5$ ) or a double overshoot (when  $x > 0.5$ ) in the grade-up composition of the SiGe buffer structure.

#### **Brief Description of the Drawings**

These and other features, objects, and advantages of the present invention will become apparent upon consideration of the following detailed description of the invention when read in conjunction with the drawing in which:

Fig. 1 is a cross section view of a layered structure illustrating one embodiment of the invention.

Fig. 2 is a SIMS graph showing the Ge concentration versus depth for the fabricated sample structure shown in Fig. 1 illustrating the preferred Ge compositional layered structure of the embodiment of the invention.

Fig. 2A is an expanded SIMS view of the upper portion of Fig. 2 to a depth of about 1000 Å showing the B and Ge concentration for the modulation-doped device region.

Fig. 3 shows data points plotted in a graph showing the hole mobility versus Ge channel width or thickness.

Fig. 4 is a detailed cross-sectional TEM of the upper device region of the fabricated sample structure shown in Fig. 2 illustrating the Ge p-channel modulation-doped device structure of the embodiment of the invention.

Fig. 5 is a graph of the measured hole mobility versus temperature in Kelvin (K) from Hall measurements and associated sheet densities.

Fig. 6 is a cross section view of a layered structure illustrating a second embodiment of the invention.

Fig. 7 is a cross section view of a layered structure illustrating a third embodiment of the invention.

Fig. 8 is a cross section view of a layered structure illustrating a fourth embodiment of the invention.

Fig. 9 is a cross section view of a layered structure illustrating a fifth embodiment of the invention.

Fig. 10 is a cross section view of a high mobility p-MODFET incorporating the layered structure of Fig. 1.

Fig. 11 is a cross section view of a Ge channel p-MOSFET incorporating the layered structure of Fig. 1.

Fig. 12 is a cross section view of a Ge CMOS MODFET device incorporating the layered structure of Fig. 1.

Fig. 13 is a cross section view of a layered structure illustrating a sixth embodiment of the invention.

Fig. 13A is a cross section view of a layered structure illustrating a seventh embodiment of the invention.

Fig. 14 is a cross section view of a Ge channel CMOS device structure for operating in an enhancement mode incorporating the layered structure of Fig. 13.

Fig. 15 is a cross section view of a Ge channel CMOS device structure having Schottky barrier metal gates.

### Description of the Preferred Embodiments

Referring to the drawing, and in particular to Fig. 1, a cross section view of a layered structure 10 for a Ge p-channel modulation-doped SiGe heterostructure is shown to illustrate the embodiment of the invention. Layers 12-18 are epitaxially grown on a single crystal semiconductor substrate 11 which may be Si, SiGe, Ge, SiC, GaAs, silicon-on-sapphire (SOS), silicon-on-insulator (SOI), Bond and Etch back Silicon On Insulator (BESOI), etc. using an epitaxial growth technique such as ultra high vacuum chemical vapor deposition (UHV-CVD), molecular beam epitaxy (MBE), or rapid thermal chemical vapor deposition (RTCVD). For a description of UHV-CVD methods for growing epitaxial Si and Si<sub>1-x</sub>Ge<sub>x</sub> films on a silicon substrate, reference is made to U.S. Patent No. 5,298,452 by B. S. Meyerson which issued Mar. 29, 1994 entitled "Method and Apparatus for Low Temperature, Low Pressure Chemical Vapor Deposition of Epitaxial Silicon Layers" which is incorporated herein by reference.

An illustration of a preferred layered structure 12' for the lower portion of layered structure 10 of layers 12C', 12B' and 12A' is shown in Fig. 2. Fig. 2 shows the corresponding Ge compositional profile of the SiGe layered structure 10 of layers 12C, 12B and 12A of Fig. 1 as measured by secondary ion mass spectroscopy (SIMS). In Fig. 2, the ordinate represents Ge concentration in atomic percent and the abscissa represents approximate depth in microns. In Fig. 2, curve portions 12A' including curve portions 21'-31', 12B' and 12C' correspond to the Ge concentration in layers 12A, 12B and 12C shown in Fig. 1.

Fig. 2A is an expanded view of just the top part of Fig. 2 showing the device region only. In Fig. 2A, the ordinate on the left side represents Ge concentration in atomic percent and the abscissa represents approximate depth in angstroms. Curve 32 shows the Ge concentration as a function of approximate depth. In Fig. 2A the ordinate on the right side represents boron



concentration in atoms/cc and curve 33 shows the boron concentration as a function of approximate depth.

The first epitaxial layer, described as layer 12A in Figs. 1 and 2, of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  alloy formed on the upper surface of substrate 11 comprised of a step-graded Ge compositional layer structure comprising layers 21-31. Layers 21-31 have a preferred profile shown in Fig. 2 where the strain has been relieved in the buffer layers 21-31 or below in substrate 11 via a modified Frank Read source as a mechanism to generate new dislocations. The Ge alloy doping profile to obtain relaxation via modified Frank Read sources is and described in U.S. Patent No. 5,659,187 which issued on Aug. 19, 1997 to F.K. Legoues and B.S. Meyerson, and is incorporated herein by reference.

Buffer layer 12 comprises layers 12A, 12B and 12C and may be initially undoped, relaxed, and have a Ge composition at interface 19 between layers 12 and 13 in the range from about 50% to about 80% with a preferred value of about 65%.

The design of layer 12 is actually made of a starting  $\text{Si}_{1-x}\text{Ge}_x$  layer 12A of a graded Ge composition formed over a Si substrate 11 follow by an overshoot layer of  $\text{Si}_{1-y}\text{Ge}_y$  layer 12B where  $y = x + z$  and  $z$  is in the range of 0.01 to 0.1 with a preferred value of 0.05 formed over layer 12A, and finally by a more relaxed  $\text{Si}_{1-z}\text{Ge}_z$  layer 12C, formed over layer 12B. Overshoot layer 12B has an overshoot of Ge concentration to provide additional stress in the layer to induce relaxation of the lattice spacing. Basically, the overshoot layer 12B functions to ensure a high degree of relaxation, i.e. >90% for the top  $\text{Si}_{1-x}\text{Ge}_x$  surface layer 12C at interface 19. In the preferred case of achieving a fully relaxed  $\text{Si}_{1-z}\text{Ge}_z$  layer 12C, it is desirable to use an overshoot

layer 12B of  $\text{Si}_{0.30}\text{Ge}_{0.70}$  as shown in Fig. 2 by curve portion 12B' with respect to curve portions 21'-31'. In relaxed  $\text{Si}_{1-m}\text{Ge}_m$  layer 12C, the in-plane lattice parameter,  $a_{\text{SiGe}}(x)$ , is given by equation (1):

$$a_{\text{SiGe}}(x) = a_{\text{Si}} + (a_{\text{Ge}} - a_{\text{Si}})x \quad (1)$$

where  $x$  is the Ge content and  $1-x$  is the Si content and  $a_{\text{Si}}$  and  $a_{\text{Ge}}$  corresponds to the lattice constant for Si and Ge respectively, and consequently in the preferred case when the top  $\text{Si}_{0.35}\text{Ge}_{0.65}$  surface layer is >90% relaxed, layer 12C would have a lattice constant which is greater than 5.02 Å.

In the case when  $\text{Si}_{1-m}\text{Ge}_m$  layer 12C has a Ge composition value  $x$  which is greater than 0.50, a double "over shoot" layered structure is preferred whereby the first "over shoot" is a  $\text{Si}_{1-m}\text{Ge}_m$  layer where  $m = 0.5x$ , and the second "over shoot" is a  $\text{Si}_{1-n}\text{Ge}_n$  layer where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1. Subsequently, in the preferred case of achieving a fully relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  as mentioned above for layer 12C, it is desirable to use a first overshoot  $\text{Si}_{1-m}\text{Ge}_m$  layer of  $\text{Si}_{0.65}\text{Ge}_{0.35}$  as shown by curve portion 28' in Fig. 2 with respect to curve portions 21'-31', and a second overshoot  $\text{Si}_{1-n}\text{Ge}_n$  layer of  $\text{Si}_{0.30}\text{Ge}_{0.70}$  as shown by curve portion 12B' in Fig. 2 with respect to curve portions 21'-31'.

Structurally, layer 12 serves to relax the strain caused by the lattice mismatch between the top surface or interface 19 of relaxed layer 12C and the underlying Si substrate 11, 31 where there is a 4.2% lattice misfit as Ge has a lattice spacing of 1.04 times larger than the lattice spacing of single crystal Si. The buffer thickness of layer 12 can range from 2.5 to 6  $\mu\text{m}$  but the preferred thickness is about 4.5  $\mu\text{m}$  with a Ge compositional profile increasing from  $x = 0$  in a preferred stepwise

fashion (compared to a continuous, linearly graded fashion) to a value in the range from  $x = 0.10$  to 1.0 with a preferred value of  $x = 0.65$  using a stepwise increase of 0.05 Ge per incremental layer as shown in Fig. 2 by layers 21'-31' with two overshoot layers of 28' and 12B'.

The preferred method of growing silicon and silicon containing films, i.e. Si:B, Si:P, SiGe, SiGe:B, SiGe:P, SiGeC, SiGeC:B, SiGeC:P is the UHV-CVD process as described in U.S. Patent 5,298,452 which issued Mar. 29, 1994 to B.S. Meyerson. A UHV-CVD reactor suitable for growing the above-mentioned silicon and silicon containing films is available from Balzers and Leybold Holding AG in Switzerland, Epigress in Sweden, and CVD Equipment Corp. in Ronkonkoma, New York, USA. For a description of additional UHV-CVD and low pressure (LP)-CVD methods for growing epitaxial Si, Si<sub>1-x</sub>Ge<sub>x</sub> and dielectrics with improved interfaces, alloy profiles and dopant profiles, reference is made to US 6,013,134 by J.O. Chu et al. which issued Jan. 11, 2000 entitled "Advanced Integrated Chemical Vacuum Deposition (AICVD) For Semiconductor" which is assigned to the assignee herein and which is incorporated herein by reference.

In layered structure 10 for a Ge p-channel modulation-doped SiGe heterostructure, a p-doped strained or relaxed SiGe layer 13 as shown in Fig. 1 is first formed over layer 12C to function as the donor or supply layer beneath an active channel. Layer 13 may have a thickness in the range from 1 to 20 nm and should have an electrically active donor dose in the range from 1 to  $5 \times 10^{12}$  cm<sup>-2</sup>. The p-doped layer 13 may be either strained or relaxed having a Ge composition in the range from 20% to <70% with a preferred composition in the range of 30% to 40% and a preferred thickness in the range from 2 to 4 nm. The p-type dopant of layer 13 may be incorporated in SiGe layer 13 by doping with different flows of B<sub>2</sub>H<sub>6</sub> during epitaxial growth of

layer 13. An example of a preferred boron dopant profile for SiGe layer 13 is shown in Fig. 2A by curve portion 33 with an integrated dose of about  $2.0 \times 10^{12}$  boron/cm<sup>2</sup>. For forming abrupt doped layers such as layer 13 with respect to adjacent layers, reference is made to Serial No. 08/885,611 filed June 30, 1997 by F. Cardone et al. entitled "Abrupt 'Delta-Like' Doping In Si and SiGe Films by UHV-CVD" which is incorporated herein by reference. An undoped SiGe layer 14 (except unwanted background doping from the CVD or other growth system) which may be strained or relaxed is epitaxially formed above p-doped layer 13 as a spacer layer. Layer 14 functions to separate the dopants in layer 13 from the active channel layer 17 to be formed above. The thickness of layer 14 should remain below the critical thickness of a SiGe layer with respect to the lattice spacing at interface 19 of relaxed layer 12. The preferred thickness of layer 14 is in the range from 2 to 4 nm with a Ge composition in the range from 25% to 30% in the case when layer 12 at interface 19 is a relaxed Si<sub>0.35</sub>Ge<sub>0.65</sub> layer. A second undoped SiGe layer 15 (except unwanted background doping from the CVD system) is epitaxially formed above layer 14 and similar to layer 13 functions as a spacer layer to further separate the dopants in layer 13 from the above Ge channel layer 17. Likewise, the thickness of layer 15 should remain below the critical thickness of a SiGe layer with respect to the lattice spacing at interface 19 of relaxed layer 12, and the preferred thickness is in the range from 1 to 3 nm with a preferred Ge composition in the range from 20% to 25% in the case when layer 12 is a relaxed Si<sub>0.35</sub>Ge<sub>0.65</sub> layer.

Next, a third undoped SiGe layer 16 (except unwanted background doping from the CVD system) is epitaxially grown over layer 15 and similar to layers 14-15, functions as a spacer layer to further separate the dopants in layer 13 from the above Ge channel 17 in order to maintain a high hole mobility in layer 17. Again similar to layers 14-15, the thickness of layer 16 should remain below the critical thickness of a SiGe layer with respect to the lattice spacing at interface

19 of relaxed layer 12. The preferred thickness of layer 16 is in the range from 1 to 4 nm with a preferred Ge composition in the range from 40% to 50% in the case when layer 12 is a relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  layer. In order to achieve device performance with high transconductances at room temperature, it is preferable to minimize the layer thicknesses of spacer layers 14-16.

A compressively-strained Ge layer 17 is epitaxially grown above layer 16 which functions as the active high mobility p-channel 33 for p-channel field effect transistors. For a detailed description of a UHV-CVD method for growing an epitaxial Ge film on a silicon substrate, reference is made to U.S. Patent No. 5,259,918 by S. Akbar, J.O. Chu, and B. Cunningham which issued Nov. 9, 1993 entitled "Heteroepitaxial Growth of Germanium on Silicon by UHV/CVD" which is incorporated herein by reference. In order for layer 17 to be an effective high mobility p-channel 39, the epitaxial Ge must be of device quality layer void of structural defects, e.g. stacking faults and any interface roughness problems between layers 16 and 17. For example, in the preferred case when layer 12C is a relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  layer at interface 19, the thickness of Ge layer 17 may be in the range from 2 to 250 Angstroms with a preferred thickness in the range of 140 to 150 Angstroms as shown in Fig. 4.

It should be noted that the preferred embodiment for the Ge channel thickness in the case when layer 12C is a relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  layer does agree with published results where the data is replotted in Fig. 3. The published data was from a publication by Y.H. Xie, D. Monroe, E.A. Fitzgerald, P.J. Silverman, F.A. Thiel, and G.P. Watson entitled "Very high mobility two-dimensional hole gas in  $\text{Si}/\text{Ge}_x\text{Si}_{1-x}/\text{Ge}$  structures grown by molecular beam epitaxy", Appl. Phys. Lett. 63 (16), 18 Oct. 1993, pp 2263-2264 which is incorporated herein by reference. In Fig. 3, the ordinate represents hole mobility  $\mu_h$  in  $\text{cm}^2/\text{Vs}$  and the abscissa represents Ge channel width or thickness in angstroms. The relationship between the measured mobility of the two-dimensional hole gas (2DHG) at 4.2K and the Ge channel thickness in a modulation-doped

heterostructure (grown by MBE) is shown in Fig. 3 where curve portion 34 represents a Ge channel layer being fabricated on a fully relaxed  $\text{Si}_{0.40}\text{Ge}_{0.60}$  buffer while curve portion 35 corresponds to a Ge channel layer which is fabricated on a relaxed  $\text{Si}_{0.30}\text{Ge}_{0.70}$  buffer layer grown on a Si substrate. The peak portion of curve 34 in Fig. 3 showing the highest hole mobility for a Ge channel fabricated on a  $\text{Si}_{0.40}\text{Ge}_{0.60}$  buffer does correspond to an optimum Ge channel width in the range from 140 to 150 angstroms which is in excellent agreement with the preferred embodiment described above. Since the preferred buffer layer 12 is a relaxed  $\text{Si}_{0.65}\text{Ge}_{0.35}$  layer as oppose to the  $\text{Si}_{0.40}\text{Ge}_{0.60}$  layer of curve 34, the actual optimum Ge channel width or thickness would be greater than 150 angstroms and may be in the range from 150 to 200 angstroms.

Fig. 4 shows a high mobility Ge channel layer 17 in a preferred embodiment describe above having stacking faults typically less than  $10^4$  defects/cm<sup>2</sup> and may be in the range from  $10^3$  to  $10^6$  defects/cm<sup>2</sup>. In Fig. 4, the smoothness of the upper surface of layer 17 at interface 36 is shown. Stacking faults are reduced to below  $10^6$  defects/cm<sup>2</sup> by the 90% relaxation of layer 12 at interface 19. A stacking fault is a planar defect in a crystal lattice stemming from a disordering in the normal stacking sequence of atom planes in the crystal lattice due to either the insertion of an extra layer of atoms or the removal of a partial atomic layer. The percent of relaxation of a layer can be determined by measuring the lattice constant such as by X-ray diffraction (XRD) techniques.

Above layer 17, a SiGe cap layer 18 is grown having the preferred Ge composition in the range from 20 to 50% and functions to separate p-channel 39 from the surface and to confine the hole carriers in layer 17. The thickness for layer 17 may range from 2 to 25 nm, with the preferred thickness in the range from 10 to 15 nm. Layers 13, 14, 15, 16, and 18 may have the same composition of silicon and germanium to provide the same lattice spacing where the Ge content

may be in the range from 20 to 70% with a preferred range from 20 to 50% in the case when layer 12C at interface 19 has a lattice spacing equivalent to a relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  buffer layer.

The channel confinement of holes and its enhanced transport mobility is a result of the higher compressive strain in the composite channel structure having a high Ge content layer with respect to the relaxed buffer layer of layer 12 at interface 19 arising from the 4.2% larger lattice constant for pure Ge relative to Si. The structural ability to create and enhance the compressive strain in the Ge channel layer formed on the relaxed SiGe buffer of layer 12 can significantly alter the conduction and valence bands of the p-channel layer of 17. Moreover, an important parameter for the design of the p-channel modulation-doped heterostructure is the valence-band offset ( $\Delta E_v$ ) of the compressively strained Ge channel layer relative to the relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epilayer of layer 12, and is given by the expression:

$$\Delta E_v = (0.74 - 0.53 x') x \text{ (eV)}$$

where  $x'$  is the Ge content of the relaxed SiGe epilayer of layer 12 and  $x$  is the Ge content in the hole channel. This formulation is reported in a publication by R. People and J.C. Bean entitled "Band alignments of coherently strained  $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$  heterostructures on  $\langle 001 \rangle$   $\text{Ge}_x\text{Si}_{1-x}$  substrates", Appl. Phys. Lett. 48 (8), 24 Feb. 1986, pp538-540 which is incorporated herein by reference. More specifically, the valence band discontinuity ( $\Delta E_v$ ) for layer 17 of a pure Ge channel formed over a relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  of layer 12 would be 396 meV which is an effective quantum well or potential barrier for hole confinement. Importantly, the compressive strain in the SiGe or Ge layer also serves to split the valence band into the heavy hole and light-hole bands whereby the hole transport in the upper valence band with the lighter hole mass for carrier

transport along the strained channel will result in enhanced hole mobilities that could be significantly higher as described below than found in Si p-channel field effect transistors which typically have a mobility of about  $75 \text{ cm}^2/\text{Vs}$  as reported in a publication by M. Rodder et al. entitled "A 1.2V,  $0.1\mu\text{m}$  Gate Length CMOS Technology: Design and Process Issues", IEDM 98-623. Consequently, the measured hole mobilities in the occupied hole band for the high mobility Ge channel 39 structure shown in Fig. 1 are in the range from 1,500 to greater than 2,000  $\text{cm}^2/\text{Vs}$  at 300K and in the range from 30,000 to greater than 50,000  $\text{cm}^2/\text{Vs}$  at 20K for the case when layer 17 is a Ge channel with a thickness in the range from 10 to 15 nm.

Furthermore in Fig. 5, curve 37, shows the measured two-dimensional hole gases (2DHG) hole mobility behavior as a function of temperature for a Ge p-channel 39 with a thickness of 138 angstroms as shown in Fig. 4 when it is properly grown on a relaxed  $\text{Si}_{0.35}\text{Ge}_{0.65}$  buffer layer 12. It is noted that when the Ge p-channel layer is grown on a lower content buffer from layer 12 of  $\text{Si}_{0.35}\text{Ge}_{0.65}$  or on an unsuitable SiGe buffer layer, a degraded mobility behavior will be observed which would be associated with a poor quality or defective Ge channel structure showing the sensitivity of the Ge p-channel 39 to the proper design of layer 12 such as the composition profile, extent of relaxation, and remaining stacking faults and misfit dislocations. In Fig. 5, the ordinate on the left side represents hole mobility  $\mu_h$  in  $\text{cm}^2/\text{Vs}$  and the abscissa represents temperature in degrees K. The measured mobilities as shown by curve 37 for a Ge p-channel 39 are a factor of 9 to 10 higher than that found in Si p-channel field effect transistors. The measured mobilities as shown by curve 37 for Ge p-channel 33 had a defect density similar to that shown in Fig. 4 and is typically in the range from  $10^3$  to  $10^6$  defects/ $\text{cm}^2$ . In Fig. 5, the ordinate on the right side represents sheet density in holes/ $\text{cm}^2$  and curve 38 shows the corresponding carrier density for the measured mobilities of curve 37 as a function of temperature. At 300K, the mobility  $\mu_h$  of Ge



p-channel 39 equals  $1,750 \text{ cm}^2/\text{Vs}$  at a sheet carrier density of  $1.62 \times 10^{12} \text{ cm}^{-2}$ . At 20K, the mobility  $\mu_h$  of Ge p-channel 39 equals  $43,954 \text{ cm}^2/\text{Vs}$  at a sheet carrier density of  $8.69 \times 10^{11} \text{ cm}^{-2}$ .

In an alternate embodiment shown in Fig. 6, either one of three spacer layers 14, 15, 16 shown in Fig. 1, for example, SiGe spacer layer 14 or SiGe spacer layer 15 or SiGe spacer layer 16 may be structurally omitted from the the Ge p-channel 17 layered structure 10 without introducing any major degradation in the hole confinement and mobility of the carriers in p-channel 39. In Fig. 6, like references are used for functions corresponding to the apparatus of Fig. 1.

In the design of a modulation-doped device 10, 80 shown in Figs. 1 and 6, a thicker spacer of spacer layers 16, 15 and 14 is usually more desirable and important when attempting to optimize the carrier mobility transport at low temperatures (i.e. less than  $< 20 \text{ K}$ ) by further separation of the active carriers in p-channel 17 from ionized hole donors in the supply layer 13. Nevertheless, for room temperature transport, there is minimal observable effect (if any at all) when only one of the three spacer layers, for example SiGe spacer 14 or SiGe spacer layer 15 or SiGe spacer layer 16 is present to space Ge channel 81 of modulation-doped device 80 from supply layer 13. Likewise, there is minimal observable effect (if any at all) when only two of the three spacers, for example a dual spacer combination of either layers 14 and 15 or layers 14 and 16 or layers 15 and 16 is present to space Ge channel 81 of modulation-doped device 80 from layer 13.

In an alternate embodiment shown in Fig. 7, layered structure 90 has a channel 40 comprising a Ge layer 17 formed above buffer layer 12. SiGe layer 16 is formed above channel 40, SiGe layer 15 is formed above layer 16, SiGe layer 14 is formed above layer 15, and the supply layer, p-doped SiGe layer 13 is formed above SiGe layer 14. A dielectric layer 41, for example, silicon

dioxide, silicon oxynitride, or aluminum oxide is formed over SiGe layer 13. In Fig. 7, like references are used for functions corresponding to the apparatus of Fig. 1.

In a layered structure 90 suitable for a modulation-doped device, supply layer 13 is situated above active channel 40 as shown in Fig. 7, the active p-channel 40 is comprised of a strained Ge layer 17 which is less than the critical thickness with respect to the lattice spacing at interface 91. Ge layer 17 is first formed on layer 12C to form interface 91. Layer 17 functions as the channel region 40 of a field effect transistor. Next, spacer layers comprised of SiGe spacer layer 14, SiGe spacer layer 15, and SiGe spacer layer 16 are grown over channel layer 17 which functions to separate the dopants in the above supply layer 13 from the below active channel layer 17, 40. Above spacer layer 14, a p-doped SiGe supply layer 13 is formed which functions as a donor layer or supply layer above active channel layer 17, 40. The germanium composition and thickness for layers 17, 16, 15, 14, and 13 may be the same or equivalent to those of like reference numbers in Fig. 1 which shows a Ge channel layered structure 10 with the SiGe supply layer 13 below channel 17, 81. In this layered structure design, the supply layer or the p-doped SiGe layer of layer 13 can be further separated above the active Ge channel of layer 17, 40 with the addition of a strained Si spacer layer between layers 16 and layer 15, or between layers 15 and layer 14, or between layers 14 and layer 13. The thickness for this additional strained Si spacer should remain below the critical thickness of a Si layer with respect to the lattice spacing at interface 91 of relaxed layer 12, and is preferred to be added between layers 14 and 13.

In an alternate embodiment shown in Fig. 8, layered structure 92 has a supply layer comprising a p-doped SiGe layer 13 formed above buffer layer 12. SiGe layer 14 is formed above supply layer 13, SiGe layer 15 is formed above layer 14, channel 42 comprising a Ge layer 17 is formed

above layer 15, SiGe layer 15' is formed above channel 42. SiGe layer 14' is formed above layer 15', and the supply layer, p-doped SiGe layer 13' is formed above SiGe layer 14'. A dielectric layer 41, for example, silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate or aluminum oxide is formed over SiGe layer 13'. In Fig. 8, like references are used for functions corresponding to the apparatus of Fig. 1.

In an alternate embodiment shown in Fig. 9, layered structure 94 has a supply layer comprising a p-doped SiGe layer 13 formed above buffer layer 12. SiGe layer 14 is formed above supply layer 13, SiGe layer 15 is formed above layer 14, SiGe layer 16 is formed above layer 15, channel 43 comprising a Ge layer 17 is formed above layer 16, SiGe layer 15' is formed above channel 43, SiGe layer 14' is formed above layer 15', and the supply layer, p-doped SiGe layer 13' is formed above SiGe layer 14'. A dielectric layer 41, for example, silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate or aluminum oxide is formed over SiGe layer 13'. In Fig. 9, like references are used for functions corresponding to the apparatus of Fig. 1.

A cross section view of a self-aligned high mobility p-MODFET device 100 is shown in Fig. 10. Self-aligned high mobility p-MODFET device 90 incorporates the layered structure of fig. 1. A self-aligned MODFET process is preferred to be used to minimize the access resistance associated with a Schottky gated device structure, and the process usually requires patterning and evaporation of the gate metalization prior to the source/drain ohmic metalization. Typically, a T-shaped gate 92 is fabricated such that the gate overhang 93 serves as a mask for the source and drain ohmic contact evaporation which prevents shorting of the source drain ohmic contacts 95 and 96 to Schottky gate 92. A Pt ohmic contact process having a low contact resistance to SiGe layers has been reported in a publication by M. Arafat, K. Ismail, J.O. Chu, M.S. Meyerson, and I.

Adesida entitled "A 70-GHz  $f_T$  Low Operating Bias Self-Aligned p-Type SiGe MODFET" -IEEE Elec. Dev. Lett., vol 17(12), Dec. 1996, pp 586-588 which is incorporated herein by reference.

The fabrication scheme for p-MODFET device 100 starts with defining the active areas via mesa isolation etching followed by evaporating or depositing of  $\text{SiO}_2$  to form the field regions 98 around the active device area. The gate structure and its patterning can be performed in a PMMA/P(MMA-MMA)/PMMA trilayer resist using electron-beam lithography followed by the evaporation and lift-off to form the T-shaped gate structure comprised of a Ti/Mo/Pt/Au metallization stack 97. A layer 101 of Ti is formed on SiGe layer 18. A layer 102 of Mo is formed over the Ti. A layer 103 of Pt is formed over layer 102 and a layer 104 of Au is formed over layer 103. Source and drain ohmic contacts 95 and 96 can be formed by evaporating Pt over T-shaped gate stack 97 followed by lift-off using an image-reversed mesa patterning process. Small gate dimensions using this fabrication scheme having a gate footprint down to 0.1- $\mu\text{m}$  has been demonstrated along with a self-aligned source/drain-to-gate distance as determined by the overhang 93 of  $\sim 0.1 \mu\text{m}$ . Self-aligned devices with a gate length of 0.1  $\mu\text{m}$  have been fabricated on high mobility strained Ge channel structures having a hole mobility of 1750  $\text{cm}^2/\text{Vs}$  (30,900  $\text{cm}^2/\text{Vs}$ ) at room temperature ( $T = 77 \text{ K}$ ) and these devices exhibited room-temperature peak extrinsic transconductances as high as 317  $\text{mS/mm}$ , at a low bias voltage of  $V_{\text{ds}} = -0.6 \text{ V}$  with a corresponding maximum voltage gain of 18. At  $T = 77 \text{ K}$ , even higher peak extrinsic transconductances of 622  $\text{mS/mm}$  have been achieved at even lower bias voltage of  $V_{\text{ds}} = -0.2 \text{ V}$ , and thus far it is believed this 77 K transconductance is the highest value ever reported for a p-type field-effect transistor.

A cross section view of a Ge channel p-type MOS-MODFET device 110 incorporating the layered structure of Fig. 1 is shown in Fig. 11. In Fig. 11, like references are used for functions corresponding to the apparatus of Figs. 1 and 10. A gate dielectric 111 such as silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium-strontium titanate or aluminum oxide may be formed above SiGe layer 18. A polysilicon layer 112 may be formed over gate dielectric 111 and patterned to form gate electrode 113 for the device structure 110. Using gate electrode 113, source region 114 and drain region 115 may be formed by ion implantation on either side of the gate electrode 113 in the layered structure 110. Source and drain ohmic contacts (not shown) can be formed by standard metallization on the upper surface of source region 114 and drain region 115. A gate sidewall spacer 116 may be formed on either side of the gate electrode 113 prior to forming the ohmic contacts.

A cross section view of a Ge complementary modulation doped (CMOD) FET device 120 is shown in Fig. 12. In Fig. 12, like references are used for functions corresponding to the apparatus of Figs. 1 and 10. Fig. 12 shows p-MODFET device 100 which is also shown in Fig. 10. Adjacent p-MODFET device 100 is n-MOS-MODFET 124. A gate dielectric 121 such as silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate or aluminum oxide may be formed above SiGe layer 18. An n<sup>+</sup> polysilicon layer 122 may be formed over gate dielectric 121 and patterned to form gate electrode 123 for the Ge n-MOS-MODFET device structure 124. Using gate electrode 123, n<sup>+</sup> source region 125 and n<sup>+</sup> drain region 126 may be formed by ion implantation on either side of the gate electrode 123 to form the Ge n-MOS-MODFET device structure 124. A gate sidewall spacer 127 may be formed on either side of the gate electrode 123 to complete the N-MOS-MODFET device structure 124. Source and

drain ohmic contacts (not shown) can be patterned and formed by standard metallization on the upper surface of source region 125 and drain region 126.

In an alternate embodiment, a near surface Ge channel layered structure 140 is shown in Fig. 13 comprising of a Ge layer 17 formed above buffer layer 12, a SiGe layer 142 formed above channel 141, and a dielectric layer 41, for example, silicon dioxide formed over SiGe layer 142 to form a near surface Ge channel layered device structure 140. In Fig 13, like references are used for functions corresponding to the apparatus of Fig. 1. In the near surface Ge channel layered structure suitable for CMOS devices, the active Ge channel 141 is first formed on layer 12C to form interface 91 and layer 17 is less than the critical thickness with respect to the lattice spacing at interface 91. Layer 17 functions as the channel region 141 of a field effect transistor. Above channel layer 141, an undoped SiGe layer 142 is formed which serves as a cap layer for forming the desired gate dielectric layer 41 in the device structure 140. To prevent the undoped SiGe layer 142 from being a parasitic channel for carriers such as electrons or holes, the preferred thickness for layer 142 is less than 1 nm. An example of a complementary Ge CMOS device structure which could be fabricated using standard process techniques is shown in Fig. 14.

Fig. 13A is a cross section view of a layered structure illustrating a modification of the embodiment shown in Fig. 13. In Fig. 13A, an additional Si layer 142' is epitaxially formed over SiGe layer 142. Gate dielectric layer 41 is formed over Si layer 142'.

A cross section view of a Ge complementary metal oxide silicon (MOS) FET device 144 is shown in Fig. 14 for enhancement mode operation. In Fig. 14, like references are used for functions corresponding to the apparatus of Figs. 1 and 12 and 13. A gate dielectric 41 such as

silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate (BST) or aluminum oxide may be formed above SiGe layer 142. A doped polysilicon layer 122' such as p+ may be formed over gate dielectric 41 and patterned to form gate electrode 123' for the Ge p-MOSFET device structure 146. Using gate electrode 123', p+ source region 125' and p+ drain region 126' may be formed by ion implantation on either side of the gate electrode 123' to form the Ge p-MOSFET device structure 146. A gate sidewall spacer 127 may be formed on either side of the gate electrode 123' to complete the p-MOSFET device structure 146. Source and drain ohmic contacts (not shown) can be patterned and formed by standard metallization on the upper surface of source region 125' and drain region 126'.

Adjacent p-MOSFET device 146 is n-MOSFET 124'. A gate dielectric 41 such as silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate or aluminum oxide may be formed above SiGe layer 142. A doped such as n<sup>-</sup> polysilicon layer 122 may be formed over gate dielectric 41 and patterned to form gate electrode 123 for the Ge n-MOSFET device structure 124'. Using gate electrode 123, n<sup>-</sup> source region 125 and n<sup>-</sup> drain region 126 may be formed by ion implantation on either side of the gate electrode 123 to form the Ge n-MOSFET device structure 124'. A gate sidewall spacer 127 may be formed on either side of the gate electrode 123 to complete the p-MOSFET device structure 124. Source and drain ohmic contacts (not shown) can be patterned and formed by standard metallization on the upper surface of source region 125 and drain region 126. Device isolation regions such as field regions 98 or deep trenches shown in Figs. 10 and 11 may be formed to separate the p-MOSFET device structure 146 from the n-MOSFET device structure 124'.

Fig. 15 is a cross section view of a Ge complementary modulation doped (CMOD) FET device 150 having Schottky barrier metal gates for enhancement mode operation. In Fig. 15, like references are used for functions corresponding to the apparatus of Figs. 1, 10 and 12-14. In Fig. 15, ohmic contacts 95 and 96 are in ohmic contact to source region 125 and drain region 126, respectively, which may be formed by ion implantation to form p<sup>+</sup> regions and are self aligned with respect to gate stack 97. Materials for transistor 100' are selected to function as a p-channel enhancement mode FET. Ohmic contacts 95' and 96' are in ohmic contact to source region 125' and drain region 126, respectively, which may be formed by ion implantation to form n-regions and are self aligned with respect to gate stack 97'. Materials for transistor 100'' are selected to function as an n-channel enhancement mode FET. While not shown, field region 98 as shown in Fig. 10 or shallow trench isolation (STI) may be used to provide isolation between transistors 100' and 100''.

With respect to transistors 100' and 100'', buried doped regions may be formed below the gate electrode and channel to adjust the threshold voltage and to reduce any parasitic currents from the adjacent device as well as from the body of the above the buried doped region.

It should be noted that in the drawing like elements or components are referred to by like and corresponding reference numerals.

While there has been described and illustrated Ge/SiGe/Si layered structures having a strained Ge channel under compression suitable for HEMT's, MOD FET's, CMOS FET's and CMOD FET's, it will be apparent to those skilled in the art that modifications and variations are



possible without deviating from the broad scope of the invention which shall be limited solely by the scope of the claims appended hereto.

Claims

Having thus described our invention, what we claim as new and desire to secure by Letters Patent is:

1. A layered structure for forming p-channel field effect transistors comprising:
  - a single crystalline substrate,
  - a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is in the range from 0.5 to 0.8,
  - a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said first layer,
  - a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,
  - a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said third layer,
  - a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fourth layer,
  - a sixth layer of Ge formed epitaxially on said fifth layer whereby said sixth layer is under compressive strain and has a thickness less than its critical thickness with respect to the upper surface of said first layer, and
  - a seventh layer of  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said sixth layer.
2. The layered structure of claim 1 further including first and second over-shoot layers,  $\text{Si}_{1-x}\text{Ge}_x$  and  $\text{Si}_{1-x}\text{Ge}_x$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5.

3. The layered structure of claim 2 wherein said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from about 0.05 to less than about 0.5.

4. The layered structure of claim 2 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

5. The layered structure of claim 1 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said sixth layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

6. The layered structure of claim 1 wherein said sixth layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

7. The layered structure of claim 1 wherein a spacer region comprises a three layer structure of said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and said fifth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

8. The layered structure of claim 7 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $a$ , where  $a = x - 0.20$  and wherein said third

layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

9. The layered structure of claim 7 wherein the Ge content of said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said fourth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

10. The layered structure of claim 7 wherein the Ge content of said fifth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $c$ , where  $c = x - 0.10$  and wherein said fifth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

11. The layered structure of claim 1 wherein said second layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed below a channel region of said sixth layer and separated therefrom by said third layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  and said fifth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said second layer is to having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and said second layer having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .

12. The layered structure of claim 1 wherein the Ge content  $x$  may be graded within said seventh layer starting with a higher Ge content nearer said sixth layer and grading down in Ge content towards the upper surface of said seventh layer with a preferred value  $x$  of 0.30.

13. A layered structure for forming p-channel field effect transistors comprising:

a single crystalline substrate,

a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is

in the range from 0.5 to 0.8,

a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said first layer,

a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,

a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said third layer,

a fifth layer of Ge formed epitaxially on said fourth layer whereby said fifth layer is

under compressive strain and has a thickness less than its critical thickness with

respect to said first layer, and

a sixth layer of  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fifth layer.

14. The layered structure of claim 13 further including two over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5 or having a preferred value of 0.65.

15. The layered structure of claim 13 wherein said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.

16. The layered structure of claim 13 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

17. The layered structure of claim 13 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said fifth layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

18. The layered structure of claim 13 wherein said fifth layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

19. The layered structure of claim 13 wherein a spacer region comprises a two layer structure of said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

20. The layered structure of claim 13 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $a$ , where  $a = x - 0.20$  and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

21. The layered structure of claim 13 wherein the Ge content of said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said fourth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

22. The layered structure of claim 19 wherein said spacer region comprising a two layer structure may be substituted with a single layer structure comprised of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer with an

adjustable thickness to allow the spacer thickness to be varied accordingly whereby the supply dose may be optimized for device applications as a function of temperature in the range from 0.4 to 425 K.

23. The layered structure of claim 13 wherein said second layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed below a channel region of said fifth layer and separated therefrom by said third layer of  $\text{Si}_{1-x}\text{Ge}_x$ , and said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said second layer having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and said second layer having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .

24. The layered structure of claim 22 wherein the supply layer of said second layer is formed and separated below the channel region of said fifth layer by said relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer.

25. The layered structure of claim 13 wherein the Ge content  $x$  may be graded within said sixth layer starting with a higher Ge content nearer said fifth layer and grading down in Ge content towards the upper surface of said sixth layer with a preferred value of 0.30.

26. A layered structure for forming p-channel field effect transistors comprising:

a single crystalline substrate,

a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is

the range from 0.5 to 0.8,

a second layer of Ge formed epitaxially on said first layer whereby said second layer is

under compressive strain and having a thickness less than its critical thickness

with respect to said first layer,

- a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,
- a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said third layer,
- a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fourth layer, and
- a sixth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fifth layer.

27. The layered structure of claim 26 further including first and second over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5 or having a preferred value of 0.65.

28. The layered structure of claim 26 wherein the first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within a strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.

29. The layered structure of claim 26 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

30. The layered structure of claim 26 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said second layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.



31. The layered structure of claim 26 wherein said second layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

32. The layered structure of claim 26 wherein a spacer region comprises a three layer structure of said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and said fifth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

33. The layered structure of claim 26 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $c$ , where  $c = x - 0.10$  and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

34. The layered structure of claim 26 wherein the Ge content of said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said fourth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

35. The layered structure of claim 26 wherein the Ge content of said fifth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $a$ , where  $a = x - 0.20$  and wherein said fifth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

36. The layered structure of claim 26 wherein said sixth layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed above a channel region of said second layer and separated therefrom by said third layer of  $\text{Si}_{1-x}\text{Ge}_x$ .

said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  and said fifth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said sixth layer having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and said sixth layer having an electrically active donor dose in the range from  $1$  to  $4 \times 10^{12} \text{ cm}^{-2}$ .

37. A layered structure for forming p-channel field effect transistors comprising:

a single crystalline substrate,

a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is the range from 0.5 to 0.8,

a second layer of Ge formed epitaxially on said first layer whereby said second layer is under compressive strain and having a thickness less than its critical thickness with respect to said first layer,

a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,

a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said third layer, and

a fifth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fourth layer.

38. The layered structure of claim 37 further including first and second over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5.

39. The layered structure of claim 37 wherein the first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within the strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.

40. The layered structure of claim 37 wherein said second over-shoot layer,  $\text{Si}_{1-x}\text{Ge}_x$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

41. The layered structure of claim 37 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said second layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

42. The layered structure of claim 37 wherein said second layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

43. The layered structure of claim 37 wherein a spacer region comprises a two layer structure of said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

44. The layered structure of claim 37 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $c$ , where  $c = x - 0.10$  and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

45. The layered structure of claim 37 wherein the Ge content of said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said fourth

layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

46. The layered structure of claim 37 wherein said fifth layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed above a channel region of said second layer and separated therefrom by said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  and said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said fifth layer having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and said sixth layer having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .

47. The layered structure of claim 43 wherein said spacer region comprising a two layer structure may be substituted with a single layer structure comprised of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer with an adjustable thickness to allow the spacer thickness to be varied accordingly whereby the supply dose may be optimized for device applications as a function of temperature in the range from 0.4 to 425 K.

48. The layered structure of claim 47 wherein the supply layer of said fifth layer is formed and separated above the channel region of said second layer by said relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer.

49. The layered structure of claim 43 wherein said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  may be substituted with a thin strained commensurate Si layer whereby a thin spacer thickness may be provided for room temperature MODFET device operation.

50. The layered structure of claim 49 wherein said fourth layer of Si is under tensile strain and is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

51. The layered structure of claim 49 wherein the supply layer of said fifth layer is formed and separated above the channel region of said second layer by said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said fourth layer of tensilely strained Si.

52. A layered structure for forming p-channel field effect transistors comprising:

a single crystalline substrate,

a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is

in the range from 0.5 to 0.8,

a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said first layer,

a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,

a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said third layer,

a fifth layer of Ge formed epitaxially on said fourth layer whereby said fifth layer is

under compressive strain and has a thickness less than its critical thickness with

respect to said first layer, and

a sixth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fifth layer,

a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said sixth layer, and

an eighth layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said seventh layer.

53. The layered structure of claim 52 further including first and second over-shoot layers,  $\text{Si}_{1-x}\text{Ge}_x$  and  $\text{Si}_{1-m}\text{Ge}_m$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5.

54. The layered structure of claim 52 wherein said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.

55. The layered structure of claim 52 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

56. The layered structure of claim 52 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said fifth layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

57. The layered structure of claim 52 wherein said fifth layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

58. The layered structure of claim 52 further including first and second spacer regions whereby said first spacer region is below the Ge channel region comprising a two layer structure of said

third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and said second spacer region is above the active Ge channel of said fifth layer comprising a similar two layer structure of said sixth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said seventh layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

59. The layered structure of claim 58 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $a$ , where  $a = x - 0.20$  and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

60. The layered structure of claim 58 wherein the Ge content of said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said fourth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

61. The layered structure of claim 58 wherein the Ge content of said sixth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $c$ , where  $c = x - 0.10$  and wherein said sixth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

62. The layered structure of claim 58 wherein the Ge content of said seventh layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said seventh layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

63. The layered structure of claim 58 wherein said spacer region comprising a two layer structure may be substituted with a single layer structure comprised of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer with an adjustable thickness to allow the spacer thickness to be varied accordingly whereby the supply dose may be optimized for device applications as a function of temperature in the range from 0.4 to 425 K.

64. The layered structure of claim 52 further including first and second supply layers whereby said first supply layer is below the Ge channel region separated by a bottom spacer region comprising a two layer structure of said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and said second supply is above the active Ge channel of said fifth layer further separated by a top spacer region comprising a similar two layer structure of said sixth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said seventh layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

65. The layered structure of claim 52 wherein said second layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed below a channel region of said fifth layer and separated therefrom by said third layer of  $\text{Si}_{1-x}\text{Ge}_x$ , and said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said second layer having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .

66. The layered structure of claim 52 wherein said eight layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed above a channel region of said fifth layer and separated therefrom by said sixth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , and said seventh layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said eight layer is to having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .



67. The layered structure of claim 52 wherein the supply layer of said second layer is formed and separated below the channel region of said fifth layer by a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer.
68. The layered structure of claim 52 wherein the supply layer of said eighth layer is formed and separated above the channel region of said fifth layer by a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer.
69. A layered structure for forming p-channel field effect transistors comprising:
- a single crystalline substrate,
  - a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is in the range from 0.5 to 0.8,
  - a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said first layer,
  - a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,
  - a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said third layer,
  - a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said fourth layer,
  - a sixth layer of Ge formed epitaxially on said fifth layer whereby said sixth layer is under compressive strain and has a thickness less than its critical thickness with respect to said first layer, and
  - a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said sixth layer,
  - a eighth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said seventh layer, and
  - a ninth layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said eighth layer.

70. The layered structure of claim 69 further including first and second over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5 or having a preferred value of 0.65.

71. The layered structure of claim 69 wherein said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.

72. The layered structure of claim 69 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

73. The layered structure of claim 69 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said sixth layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

74. The layered structure of claim 69 wherein said sixth layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

75. The layered structure of claim 69 further including first and second spacer regions whereby said first spacer region is below the Ge channel region comprising a three layer structure of said

third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and said fifth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and the second spacer region is above the active Ge channel of said sixth layer comprising a dissimilar two layer structure of said seventh layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said eighth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

76. The layered structure of claim 69 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $a$ , where  $a = x - 0.20$  and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

77. The layered structure of claim 69 wherein the Ge content of said fourth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said fourth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

78. The layered structure of claim 69 wherein the Ge content of said fifth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $c$ , where  $c = x - 0.10$  and wherein said fifth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

79. The layered structure of claim 69 wherein the Ge content of said seventh layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of  $c$ , where  $c = x - 0.10$  and wherein said seventh layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

80. The layered structure of claim 69 wherein the Ge content of said eighth layer of  $\text{Si}_{1-x}\text{Ge}_x$  is the range from 0.5 to 0.8 with a preferred content of  $b$ , where  $b = x - 0.25$  and wherein said eighth layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

81. The layered structure of claim 75 wherein said bottom spacer region comprising a three layer structure may be substituted with a single layer structure comprised of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer with an adjustable thickness to allow the spacer thickness to be varied accordingly whereby the supply dose may be optimized for device applications as a function of temperature in the range from 0.4 to 425 K.

82. The layered structure of claim 75 wherein said top spacer region comprising a two layer structure may be substituted with a single layer structure comprised of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer with an adjustable thickness to allow the spacer thickness to be varied accordingly whereby the supply dose may be optimized for device applications as a function of temperature in the range from 0.4 to 425 K.

83. The layered structure of claim 75 wherein said both top and bottom spacer regions may be substituted with a single layer structure comprised of a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer with an adjustable thickness to allow the spacer thickness to be varied accordingly whereby the supply dose may be optimized for device applications as a function of temperature in the range from 0.4 to 425 K.

84. The layered structure of claim 69 further including first and second supply layers whereby said first supply layer is below the Ge channel region separated by a bottom spacer region comprising a three layer structure of said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , and said fifth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ ; and said second supply is above the active Ge channel of said sixth layer further separated by a top spacer region comprising a dissimilar two layer structure of said seventh layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said eighth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ .

85. The layered structure of claim 69 wherein said second layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed below a channel region of said sixth layer and separated therefrom by said third layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , said fourth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  and said fifth layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$ , said second layer having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .

86. The layered structure of claim 69 wherein said ninth layer is a p-doped  $\text{Si}_{1-x}\text{Ge}_x$  layer formed above a channel region of said sixth layer and separated therefrom by said seventh layer of  $\text{Si}_{1-x}\text{Ge}_x$ , and said eighth layer of  $\text{Si}_{1-x}\text{Ge}_x$ , said ninth layer is to having a thickness in the range from 1 to 20 nm with a preferred thickness from 4 to 5 nm and having an electrically active donor dose in the range from 1 to  $4 \times 10^{12} \text{ cm}^{-2}$ .

87. The layered structure of claim 69 wherein the supply layer of said second layer is formed and separated below the channel region of said fifth layer by a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer.

88. The layered structure of claim 69 wherein the supply layer of said eight layer is formed and separated above the channel region of said fifth layer by a relaxed  $\text{Si}_{1-x}\text{Ge}_x$  layer.

89. A layered structure for forming a Ge channel field effect transistors comprising:

a single crystalline substrate,

a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is

the range from 0.5 to 0.8,

a second layer of Ge formed epitaxially on said first layer whereby said second layer is

under compressive strain and having a thickness less than its critical thickness

with respect to said first layer,

a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer, and

a fourth layer of gate dielectric formed on said third layer.

90. The layered structure of claim 89 further including first and second over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5.

91. The layered structure of claim 89 wherein said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.

92. The layered structure of claim 89 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

93. The layered structure of claim 89 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said second layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

94. The layered structure of claim 89 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of 0.30 and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer with a thickness equal to or less than 1 nm.

95. The layered structure of claim 89 wherein the Ge content  $x$  may be graded within said third layer starting with a higher Ge content nearer said second layer and grading down in Ge content towards the upper surface of said third layer to a value of about 0.30.

96. The layered structure of claim 89 wherein the gate dielectric of said fourth layer is a dielectric material selected from the group consisting of silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate, aluminum oxide and combinations thereof.

97. The layered structure of claim 89 wherein said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  may be substituted with a thin strained commensurate Si layer suitable for high temperature oxidation in formation of a high quality silicon dioxide layer in said fourth layer of gate dielectric.

98. The layered structure of claim 97 wherein said third layer of Si is under tensile strain and is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.
99. A layered structure for forming a Ge channel field effect transistor comprising:
- a single crystalline substrate,
  - a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is the range from 0.5 to 0.8,
  - a second layer of Ge formed epitaxially on said first layer whereby said second layer is under compressive strain and having a thickness less than its critical thickness with respect to said first layer,
  - a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,
  - a fourth layer of undoped Si formed epitaxially on said third layer, and
  - a fifth layer of gate dielectric formed on said fourth layer.
100. The layered structure of claim 99 further including first and second over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5.
101. The layered structure of claim 99 wherein said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer has a Ge fraction  $m$ , where  $m$  is the range from 0.05 to less than 0.5.
102. The layered structure of claim 99 wherein said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer has a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range



from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

103. The layered structure of claim 99 wherein the active device region is a buried channel made up of an epitaxial Ge channel of said second layer having a higher compressive strain to provide a deeper quantum well or a higher barrier for better hole confinement with no alloy scattering as compared to a single SiGe layer channel device alone.

104. The layered structure of claim 99 wherein said second layer is formed at temperatures where 3D growth of Ge films does not occur to generate interface roughness problems and at a temperature range from 275° - 350° C where 2D growth of Ge films does occur.

105. The layered structure of claim 99 wherein the Ge content of said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  is in the range from 0.5 to 0.8 with a preferred content of 0.30 and wherein said third layer is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer with a thickness equal to or less than 1 nm.

106. The layered structure of claim 99 wherein the Ge content  $x$  may be graded within said third layer starting with a higher Ge content nearer said second layer and grading down in Ge content towards the upper surface of said third layer to a value of about 0.30.

107. The layered structure of claim 99 wherein the gate dielectric of said fourth layer is a dielectric material selected from the group consisting of silicon dioxide, silicon oxynitride, silicon nitride, tantalum oxide, barium strontium titanate, aluminum oxide and combinations thereof.

108. The layered structure of claim 99 wherein said third layer of  $\text{Si}_{1-x}\text{Ge}_x$  may be substituted with a thin strained commensurate Si layer suitable for high temperature oxidation in formation of a high quality silicon dioxide layer in said fourth layer of gate dielectric.

109. The layered structure of claim 99 wherein said fourth layer of Si is under tensile strain and is commensurate having a thickness below its critical thickness with respect to said first layer at its interface with said second layer.

110. A layered structure for forming a field effect transistor comprising:

- a single crystalline substrate,
- a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said substrate where Ge fraction  $x$  is the range from 0.5 to 0.8,
- a second layer of Ge formed epitaxially on said first layer whereby said second layer is under compressive strain and having a thickness less than its critical thickness with respect to said first layer,
- a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  formed epitaxially on said second layer,
- a first Schottky gate electrode formed on said third layer,
- a first source region of a first type formed and located on one side of said first gate electrode, and
- a first drain region of a first type formed and located on the other side of said first gate electrode whereby a first field-effect transistor structure is formed of a first type.

111. The layered structure of claim 110 further including,

electrical isolation regions created by the selective removal of at least said third layer through said second layer,

a second Schottky gate electrode formed on said third layer positioned with respect to said electrical isolation regions to be electrically isolated from said first field-effect transistor structure,

a second source region of a second type formed and located on one side of said second gate electrode, and

a second drain region of a second type formed and located on the other side of said second gate electrode whereby a second field-effect transistor structure is formed of a second type.

112. The layered structure of claim 1 further including,

electrical isolation regions created by the selective removal of at least said seventh layer through said second layer,

a Schottky gate electrode formed on said seventh layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

113. The layered structure of claim 13 further including,

electrical isolation regions created by the selective removal of at least said sixth layer through said second layer,

a Schottky gate electrode formed on said sixth layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

114. The layered structure of claim 26 further including,

electrical isolation regions created by the selective removal of at least said sixth

layer through said second layer,

a Schottky gate electrode formed on said sixth layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

115. The layered structure of claim 37 further including,

electrical isolation regions created by the selective removal of at least said fifth

layer through said second layer,

a Schottky gate electrode formed on said fifth layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

116. The layered structure of claim 52 further including,

electrical isolation regions created by the selective removal of at least said seventh

layer through said second layer,

a Schottky gate electrode formed on said seventh layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

117. The layered structure of claim 69 further including,

electrical isolation regions created by the selective removal of at least said eighth layer through said second layer,

a Schottky gate electrode formed on said eighth layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

118. The layered structure of claim 1 further including,

electrical isolation regions created by the selective removal of at least said seventh layer through said second layer,

a gate dielectric formed on said seventh layer,

a gate electrode formed on said gate dielectric,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

119. The layered structure of claim 13 further including,

electrical isolation regions created by the selective removal of at least said sixth layer through said second layer,

a gate dielectric formed on said sixth layer,

a gate electrode formed on said gate dielectric,  
a source electrode formed and located on one side of said gate electrode, and  
a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

120. The layered structure of claim 26 further including,

electrical isolation regions created by the selective removal of at least said sixth layer through said second layer,  
a gate dielectric formed on said sixth layer,  
a gate electrode formed on said gate dielectric,  
a source electrode formed and located on one side of said gate electrode, and  
a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

121. The layered structure of claim 37 further including,

electrical isolation regions created by the selective removal of at least said fifth layer through said second layer,  
a gate dielectric formed on said fifth layer,  
a gate electrode formed on said gate dielectric,  
a source electrode formed and located on one side of said gate electrode, and  
a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

122. The layered structure of claim 52 further including,

electrical isolation regions created by the selective removal of at least said seventh

layer through said second layer,

a gate dielectric formed on said seventh layer,

a gate electrode formed on said gate dielectric,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

123. The layered structure of claim 69 further including,

electrical isolation regions created by the selective removal of at least said eighth

layer through said second layer,

a gate dielectric formed on said eighth layer,

a gate electrode formed on said gate dielectric,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

124. The layered structure of claim 89 further including,

electrical isolation regions created by the selective removal of at least said fourth layer

through said second layer,

a gate electrode formed on said gate dielectric of said fourth layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

125. The layered structure of claim 99 further including,

electrical isolation regions created by the selective removal of at least said fifth layer through said second layer,

a gate electrode formed on said gate dielectric of said fifth layer,

a source electrode formed and located on one side of said gate electrode, and

a drain electrode formed and located on the other side of said gate electrode whereby a field-effect transistor structure is formed.

126. A method for forming p-channel field effect transistors comprising the steps of:

selecting a single crystalline substrate,

forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is in the range from 0.5 to 0.8,

forming a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said first layer,

forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,

forming a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said third layer,

forming a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fourth layer,

forming a sixth layer of Ge epitaxially on said fifth layer whereby said sixth layer is under compressive strain and has a thickness less than its critical thickness with respect to the upper surface of said first layer, and

forming a seventh layer of  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said sixth layer.



127. The method of claim 126 further including the steps of forming first and second over-shoot layers,  $\text{Si}_{1-m}\text{Ge}_m$  and  $\text{Si}_{1-n}\text{Ge}_n$ , within a strain relief structure of said first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  for the case when  $x$  is greater than 0.5.

128. The method of claim 127 wherein said step of forming said first over-shoot layer,  $\text{Si}_{1-m}\text{Ge}_m$ , within said strain relief structure of said first layer includes forming a Ge fraction  $m$ , where  $m$  is the range from about 0.05 to less than about 0.5.

129. The method of claim 127 wherein said step of forming said second over-shoot layer,  $\text{Si}_{1-n}\text{Ge}_n$ , within the strain relief structure of said first layer includes forming a Ge fraction  $n$ , where  $n = x + z$  and  $z$  is in the range from 0.01 to 0.1, and having a thickness less than its critical thickness with respect to said first layer.

130. A method for forming p-channel field effect transistors comprising the steps of:

selecting a single crystalline substrate,

forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is in the range from 0.5 to 0.8,

forming a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said first layer,

forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,

forming a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said third layer,

forming a fifth layer of Ge epitaxially on said fourth layer whereby said fifth layer is

under compressive strain and has a thickness less than its critical thickness with respect to said first layer, and

forming a sixth layer of  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fifth layer.

131. A method for forming p-channel field effect transistors comprising the steps of:
- selecting a single crystalline substrate,
  - forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is the range from 0.5 to 0.8,
  - forming a second layer of Ge epitaxially on said first layer whereby said second layer is under compressive strain and having a thickness less than its critical thickness with respect to said first layer,
  - forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,
  - forming a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said third layer,
  - forming a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fourth layer, and
  - forming a sixth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fifth layer.
132. A method for forming p-channel field effect transistors comprising the steps of:
- selecting a single crystalline substrate,
  - forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is the range from 0.5 to 0.8,
  - forming a second layer of Ge epitaxially on said first layer whereby said second layer is under compressive strain and having a thickness less than its critical thickness with respect to said first layer,
  - forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,
  - forming a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said third layer, and
  - forming a fifth layer of p-doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fourth layer.

133. A method for forming p-channel field effect transistors comprising the steps of:

selecting a single crystalline substrate,

forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is in the range from 0.5 to 0.8,

forming a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said first layer,

forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,

forming a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said third layer,

forming a fifth layer of Ge epitaxially on said fourth layer whereby said fifth layer is under compressive strain and has a thickness less than its critical thickness with respect to said first layer, and

forming a sixth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fifth layer,

forming a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said sixth layer, and

forming an eighth layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said seventh layer.

134. A method for forming p-channel field effect transistors comprising the steps of:

selecting a single crystalline substrate,

forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is in the range from 0.5 to 0.8,

forming a second layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said first layer,

forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,

forming a fourth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said third layer,

forming a fifth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said fourth layer,

forming a sixth layer of Ge epitaxially on said fifth layer whereby said sixth layer is

under compressive strain and has a thickness less than its critical thickness with

respect to said first layer, and  
forming a seventh layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said sixth layer,  
forming a eighth layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said seventh layer, and  
forming a ninth layer of doped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said eighth layer.

135. A method for forming a Ge channel field effect transistor comprising the steps of:

selecting a single crystalline substrate,  
forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is  
the range from 0.5 to 0.8,  
forming a second layer of Ge epitaxially on said first layer whereby said second layer is  
under compressive strain and having a thickness less than its critical thickness  
with respect to said first layer,  
forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer, and  
forming a fourth layer of gate dielectric on said third layer.

136. A method for forming a Ge channel field effect transistor comprising the steps of:

selecting a single crystalline substrate,  
forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is  
the range from 0.5 to 0.8,  
forming a second layer of Ge epitaxially on said first layer whereby said second layer is  
under compressive strain and having a thickness less than its critical thickness  
with respect to said first layer,  
forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,  
forming a fourth layer of undoped Si epitaxially on said third layer, and

forming a fifth layer of gate dielectric on said fourth layer.

137. A method for forming a field effect transistor comprising the steps of:

selecting a single crystalline substrate,

forming a first layer of relaxed  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said substrate where Ge fraction  $x$  is the range from 0.5 to 0.8,

forming a second layer of Ge epitaxially on said first layer whereby said second layer is under compressive strain and having a thickness less than its critical thickness with respect to said first layer,

forming a third layer of undoped  $\text{Si}_{1-x}\text{Ge}_x$  epitaxially on said second layer,

forming a first Schottky gate electrode on said third layer,

forming a first source region of a first type and located on one side of said first gate electrode, and

forming a first drain region of a first type and located on the other side of said first gate electrode whereby a first field-effect transistor structure is formed of a first type.

138. The method of claim 137 further including the steps of.

forming electrical isolation regions by the selective removal of at least said third layer through said second layer,

forming a second Schottky gate electrode on said third layer positioned with respect to said electrical isolation regions to be electrically isolated from said first field-effect transistor structure,

forming a second source region of a second type and located on one side of said second gate electrode, and

forming a second drain region of a second type and located on the other side of said second gate electrode whereby a second field-effect transistor structure is formed of a second type.

139. The method of claim 126 further including the steps of,

forming a first Schottky gate electrode on said seventh layer,

forming a first source electrode and located on one side of said first gate electrode, and

forming a first drain electrode and located on the other side of said first gate electrode

whereby a first field-effect transistor structure is formed.

140. The method of claim 139 further including the steps of,

forming electrical isolation regions by the selective removal of at least said seventh layer through said second layer,

forming a second gate dielectric on said seventh layer,

forming a second gate electrode on said gate dielectric,

forming a second source electrode and located on one side of said second gate electrode,

and

forming a second drain electrode on the other side of said second gate electrode whereby a second field-effect transistor structure is formed.

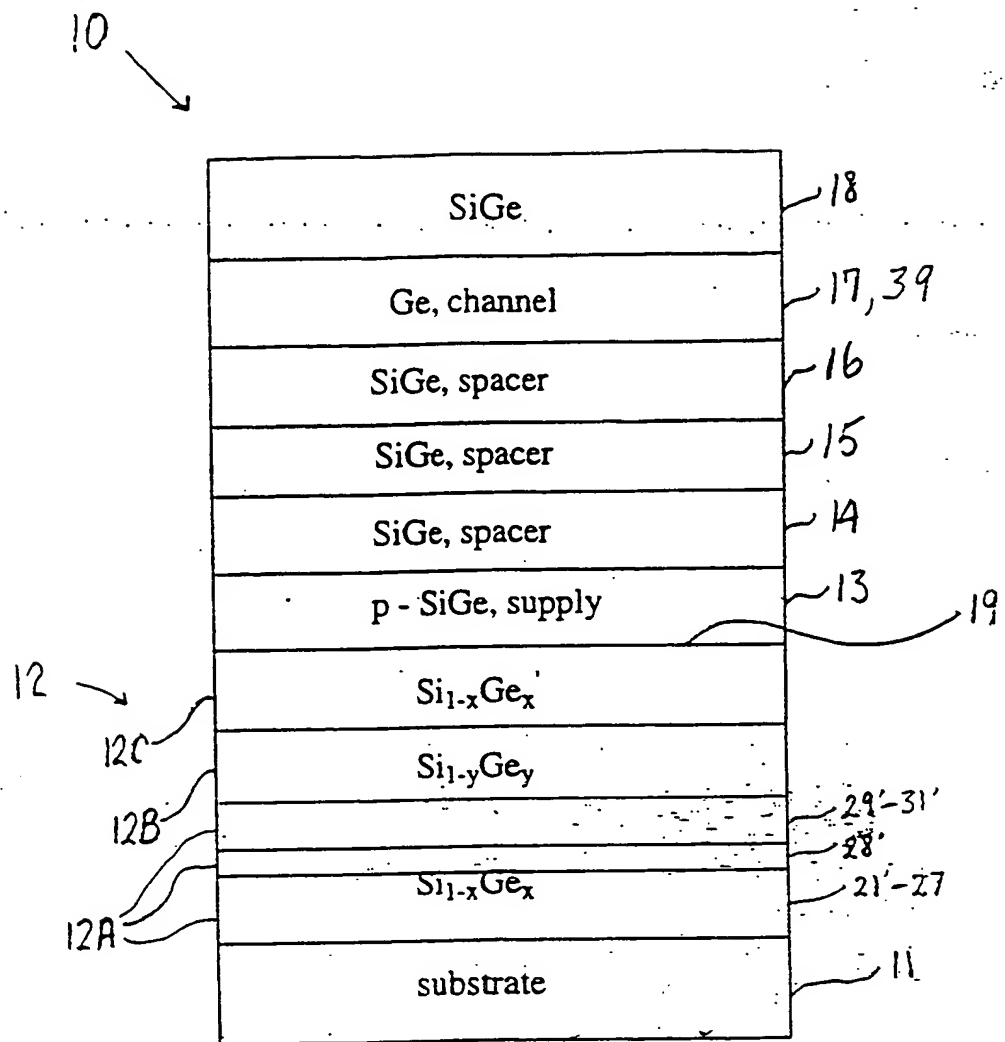


Fig. 1

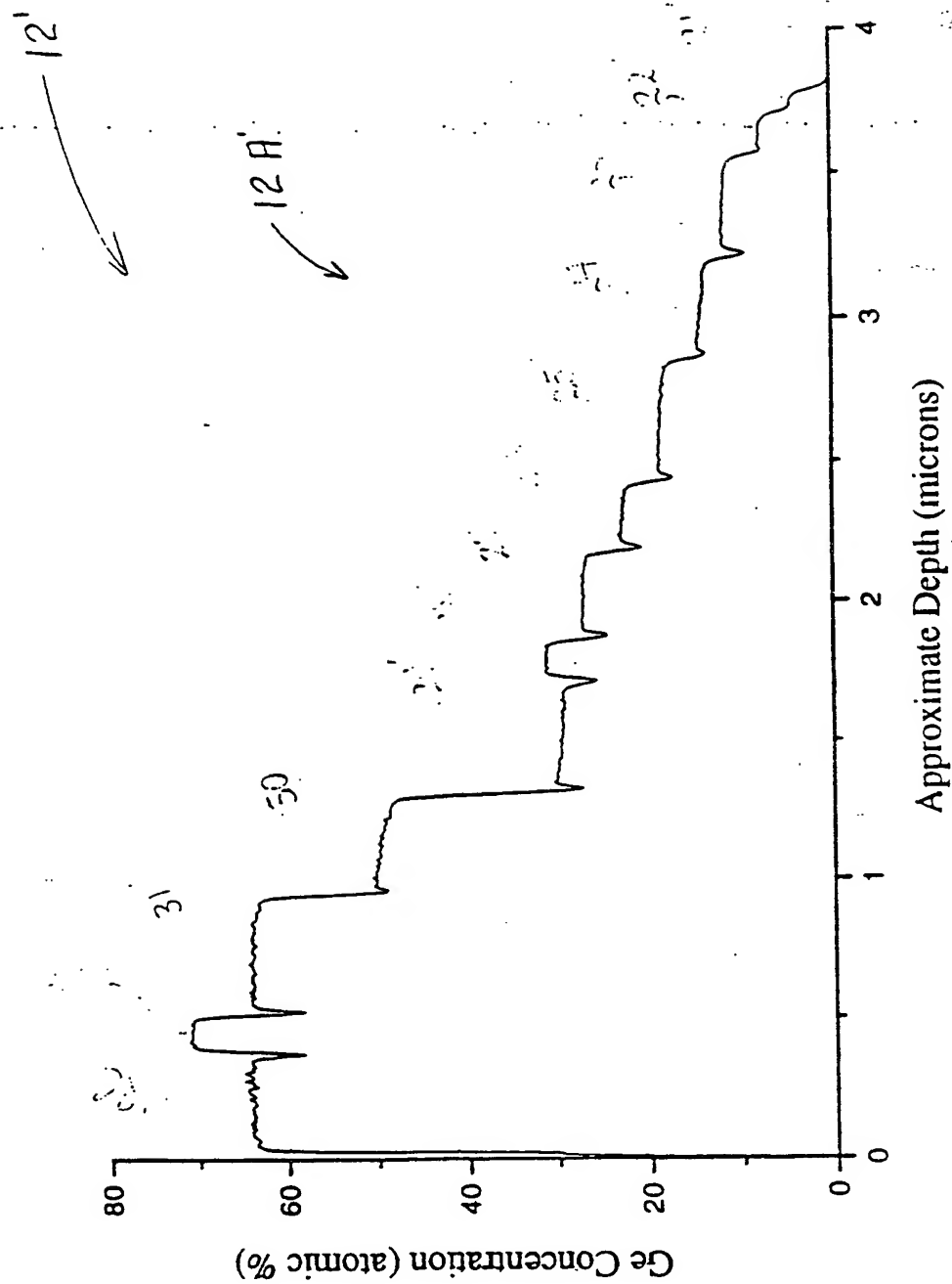


Fig. 2



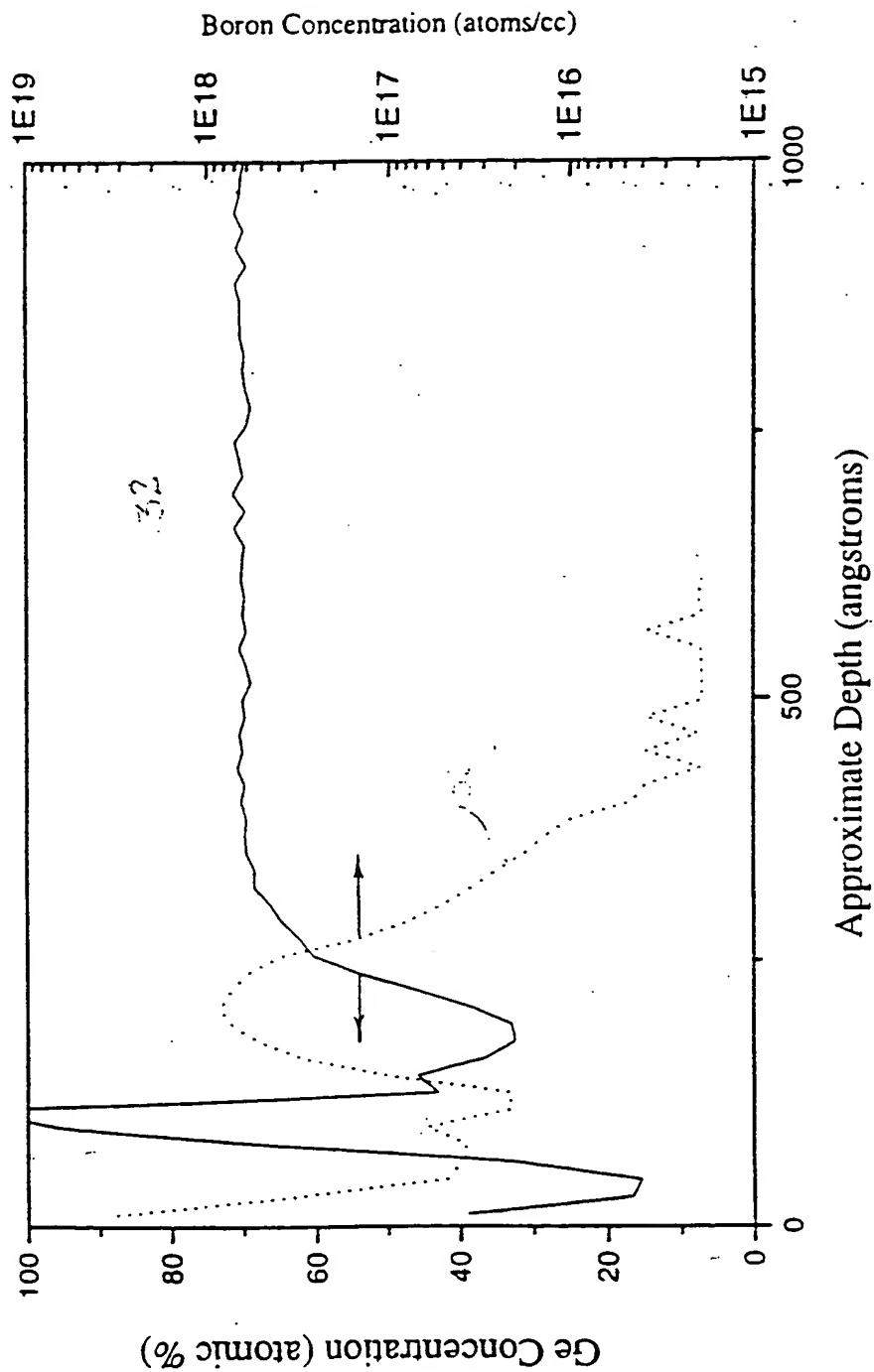


Fig 2A

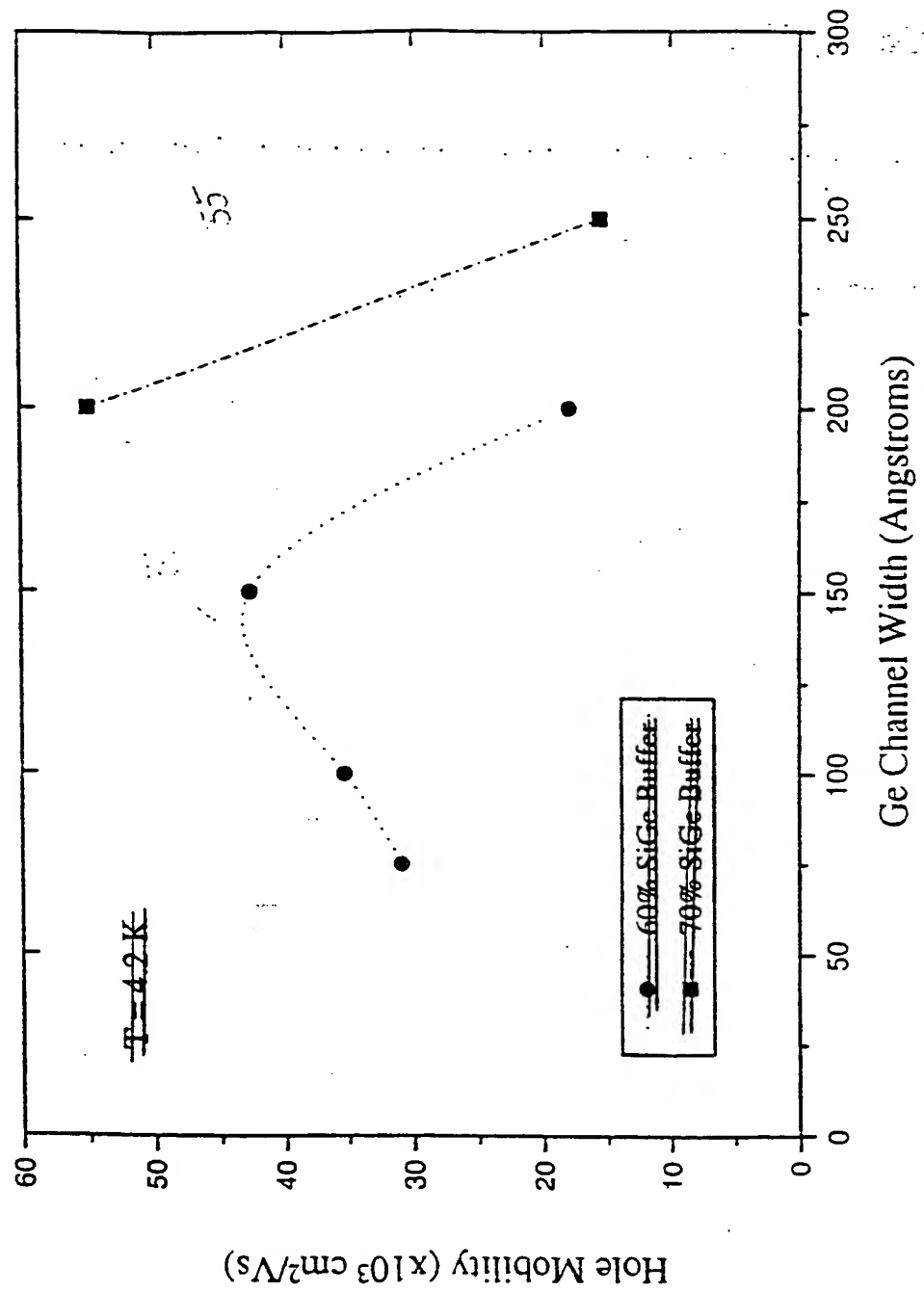


Fig. 3

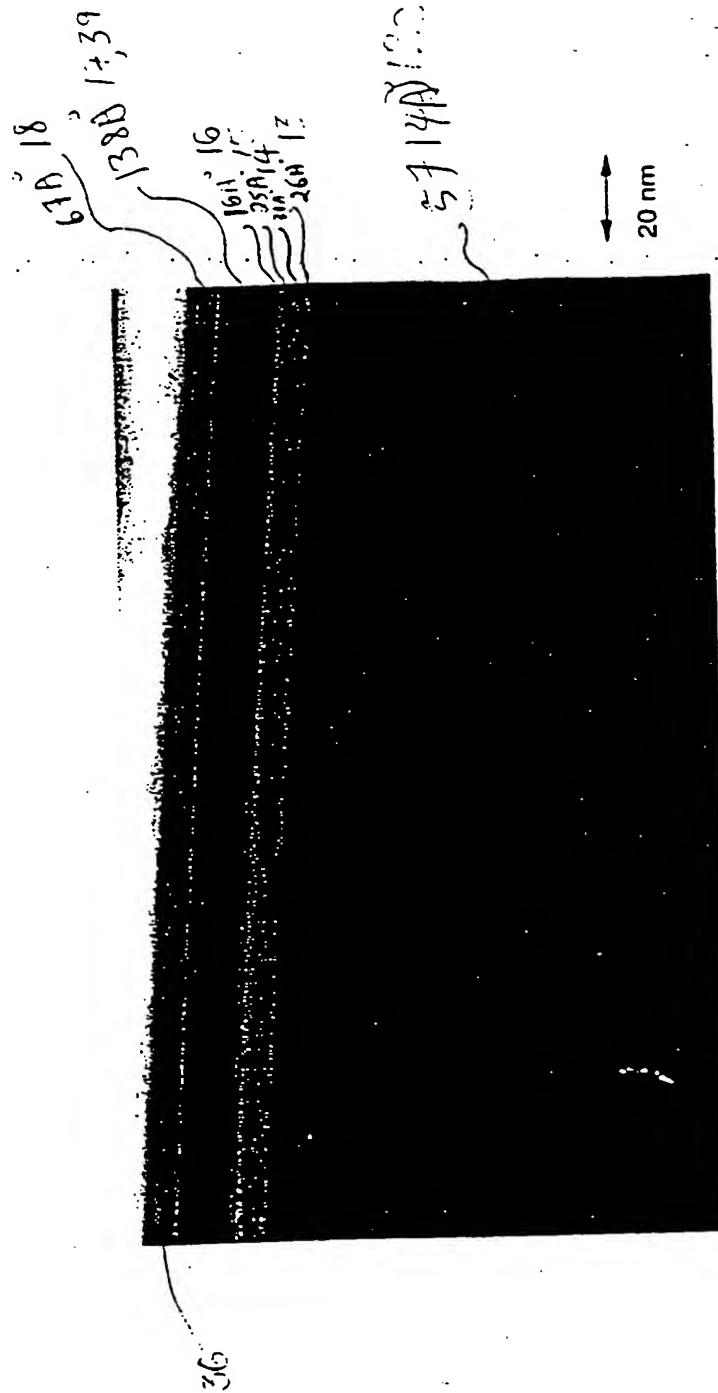


Fig 4

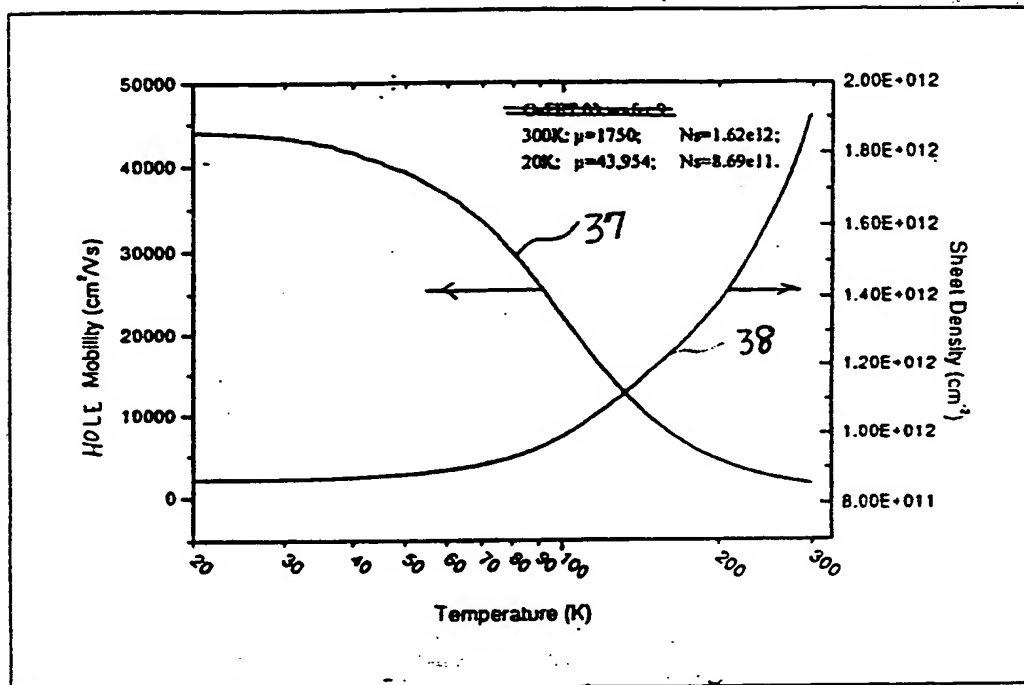
~~GeFET 03 Wafer 9~~

Fig 5

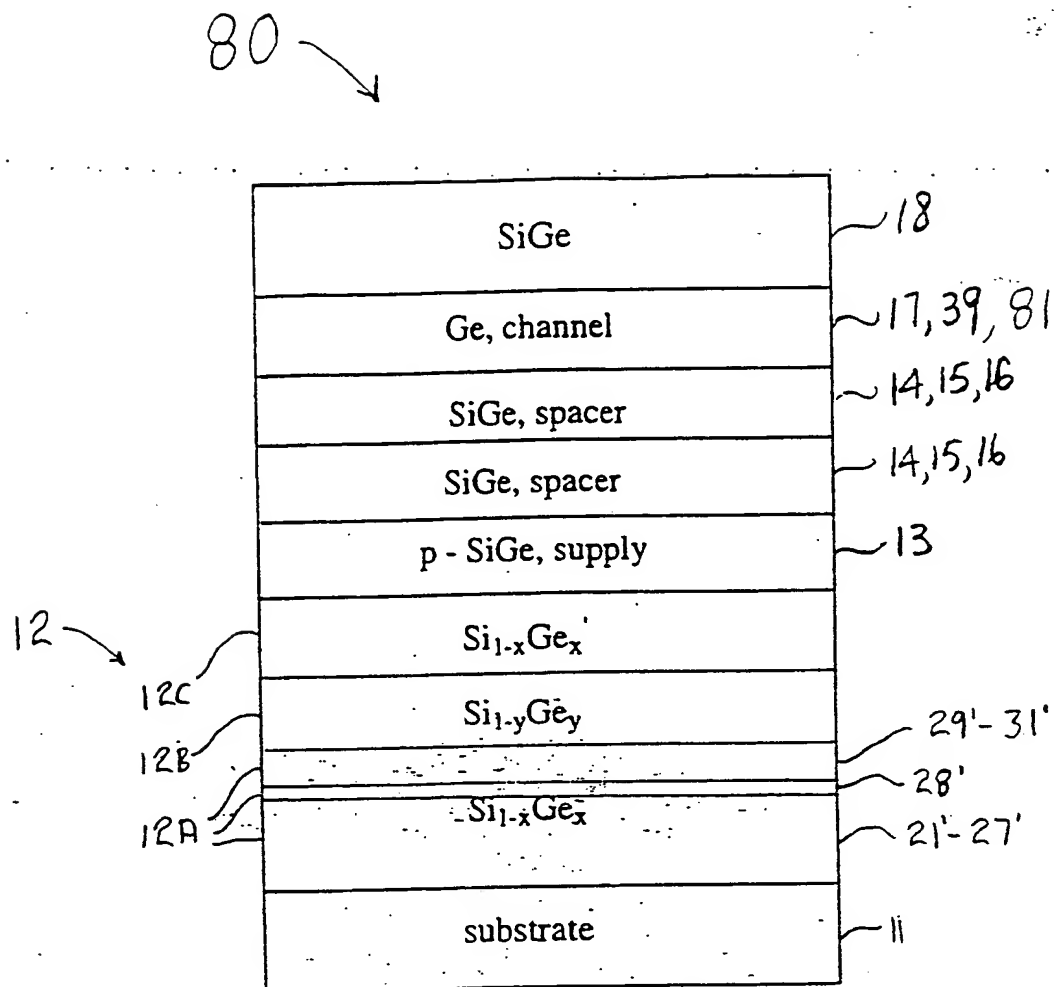


Fig. 6

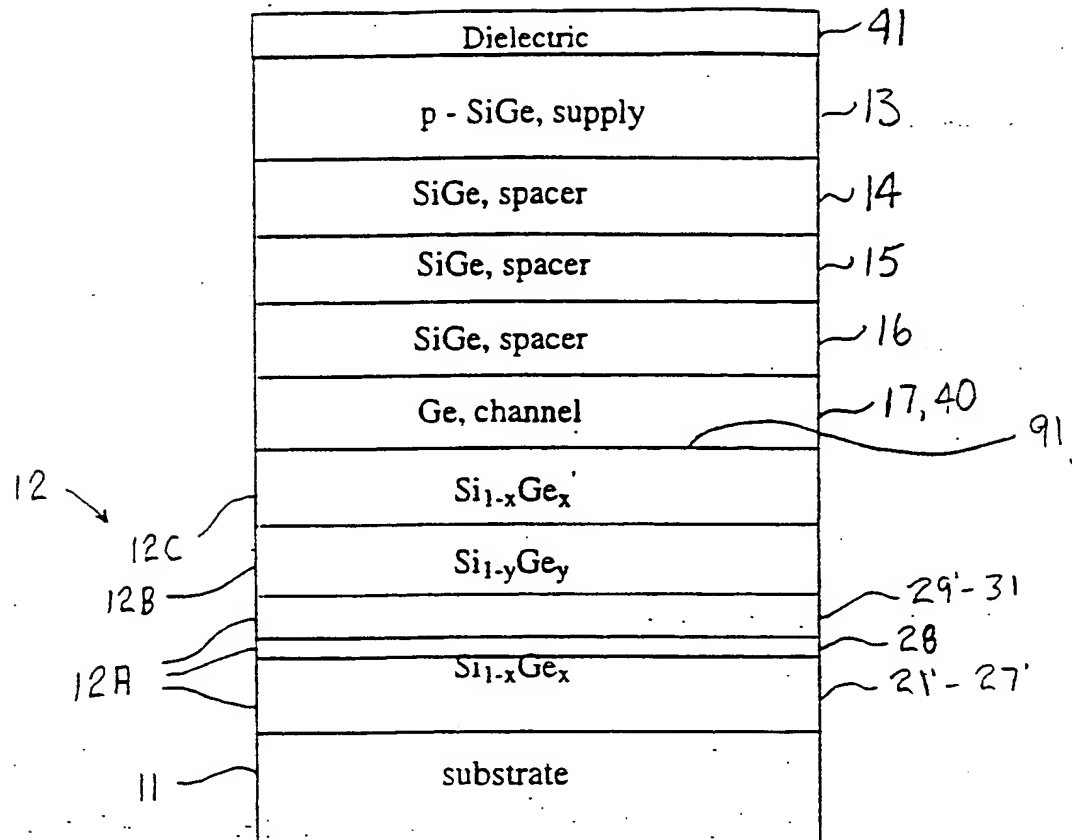


Fig. 7

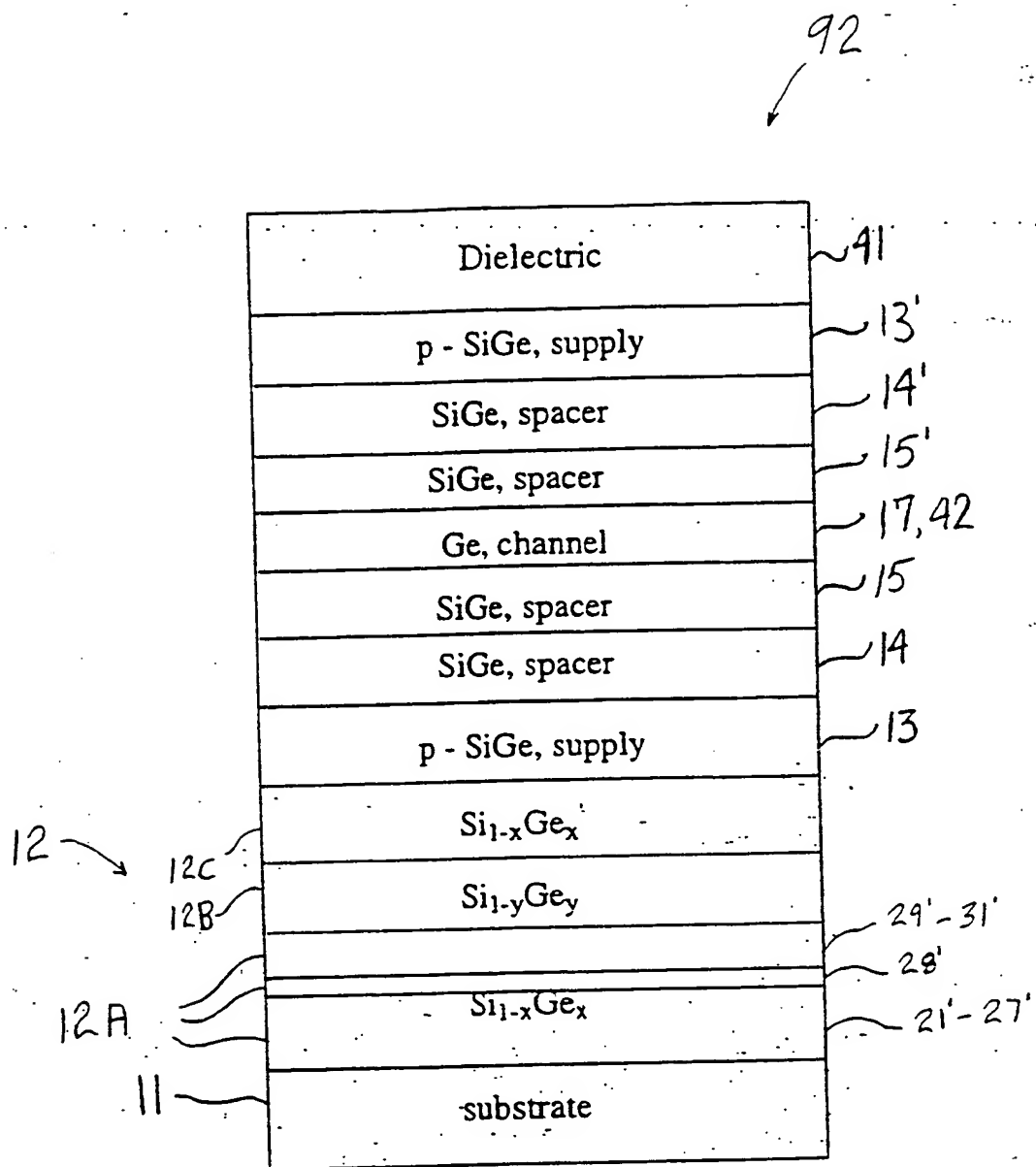


Fig. 8

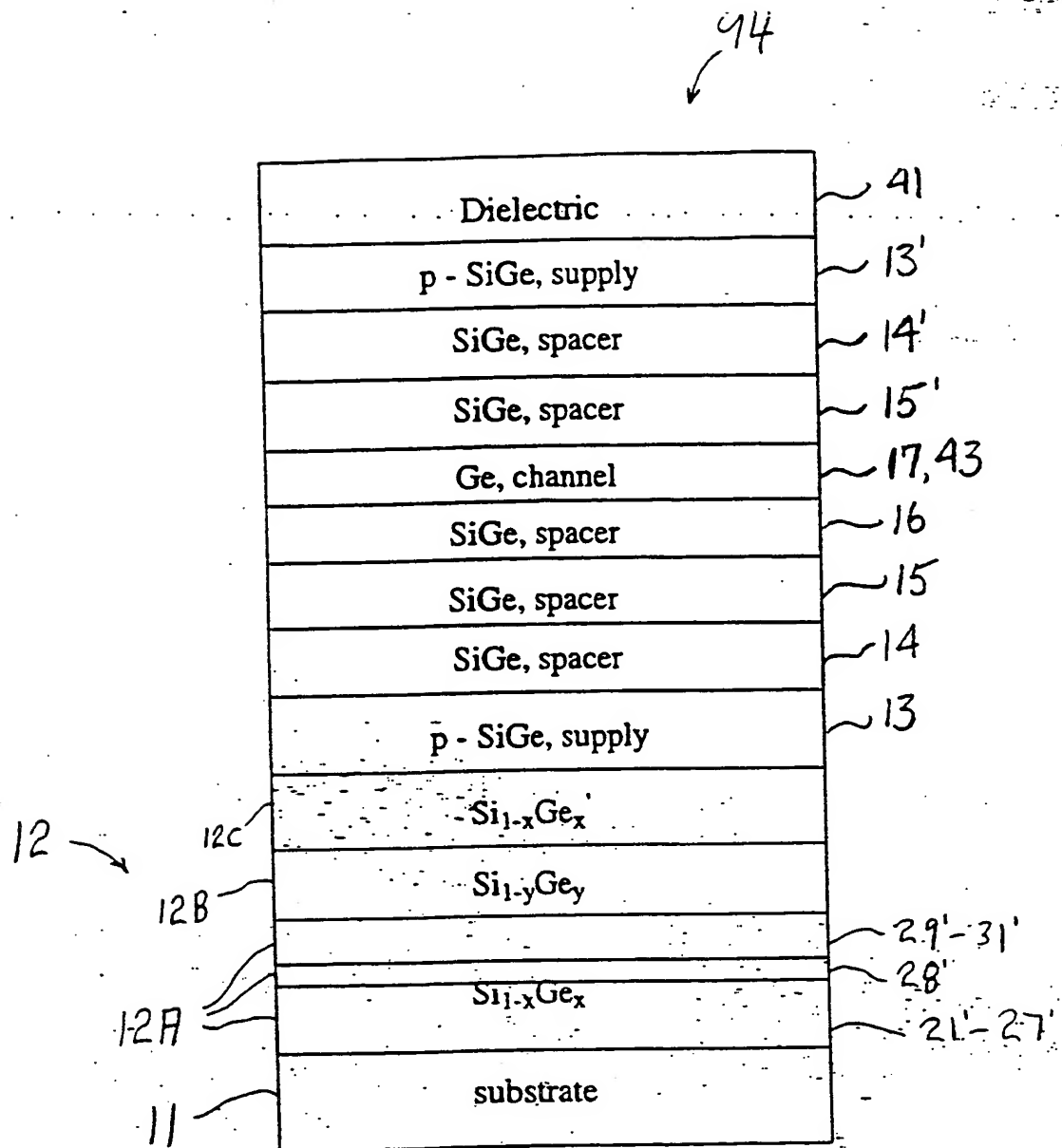


Fig. 9



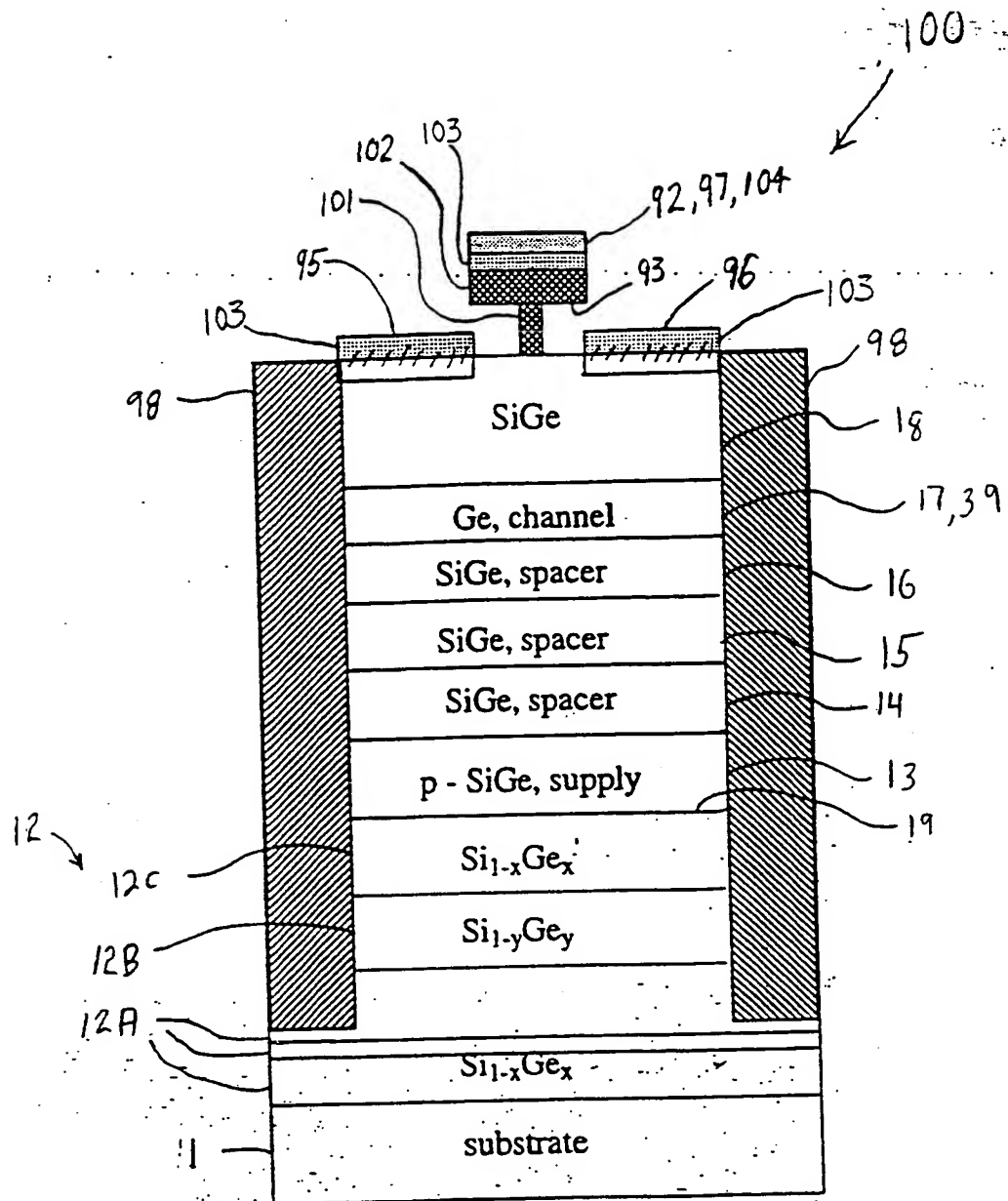


Fig. 10

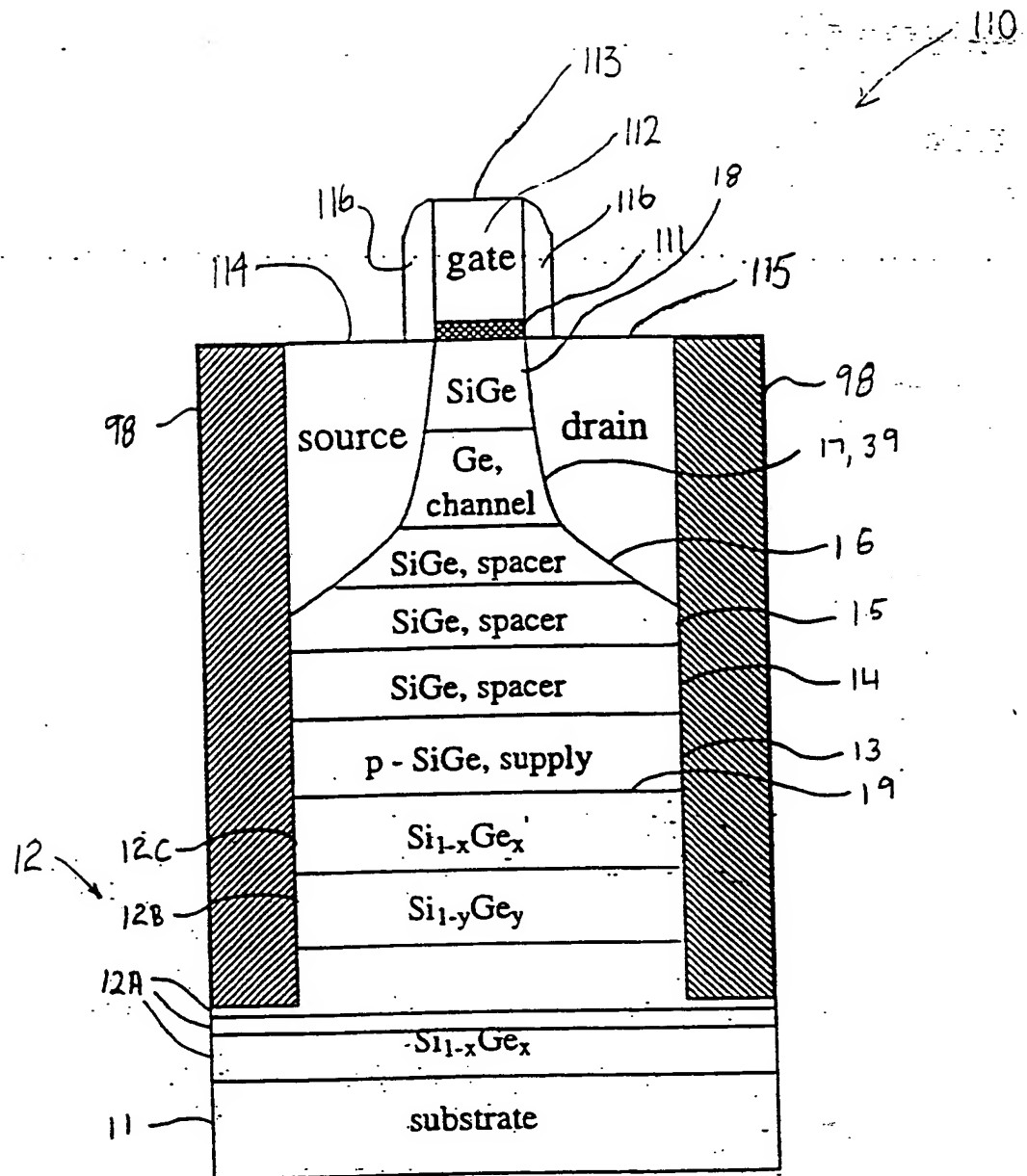


Fig. 11

~~Ge-Complementary-Hybrid-Structure~~

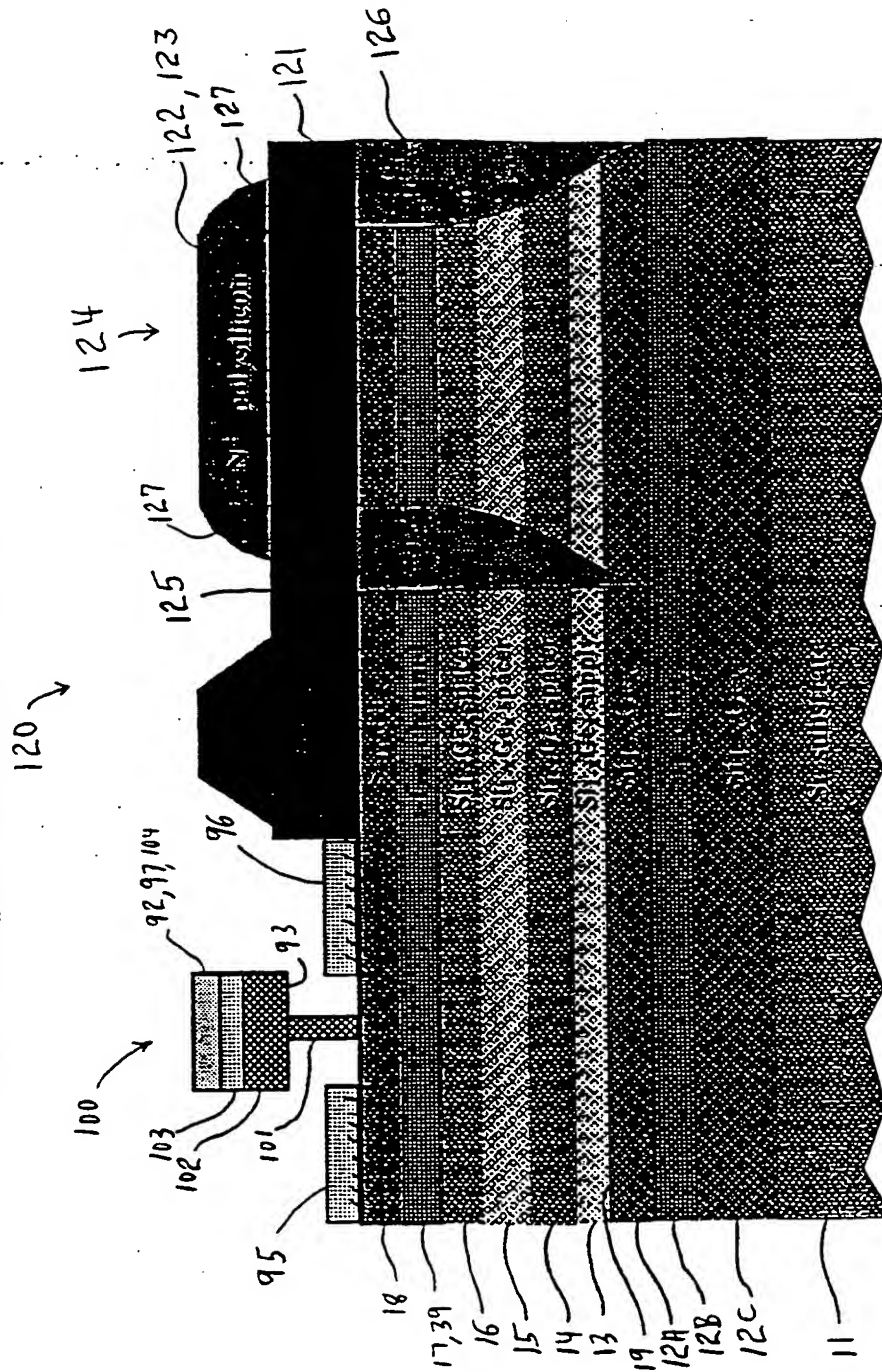


Fig 12

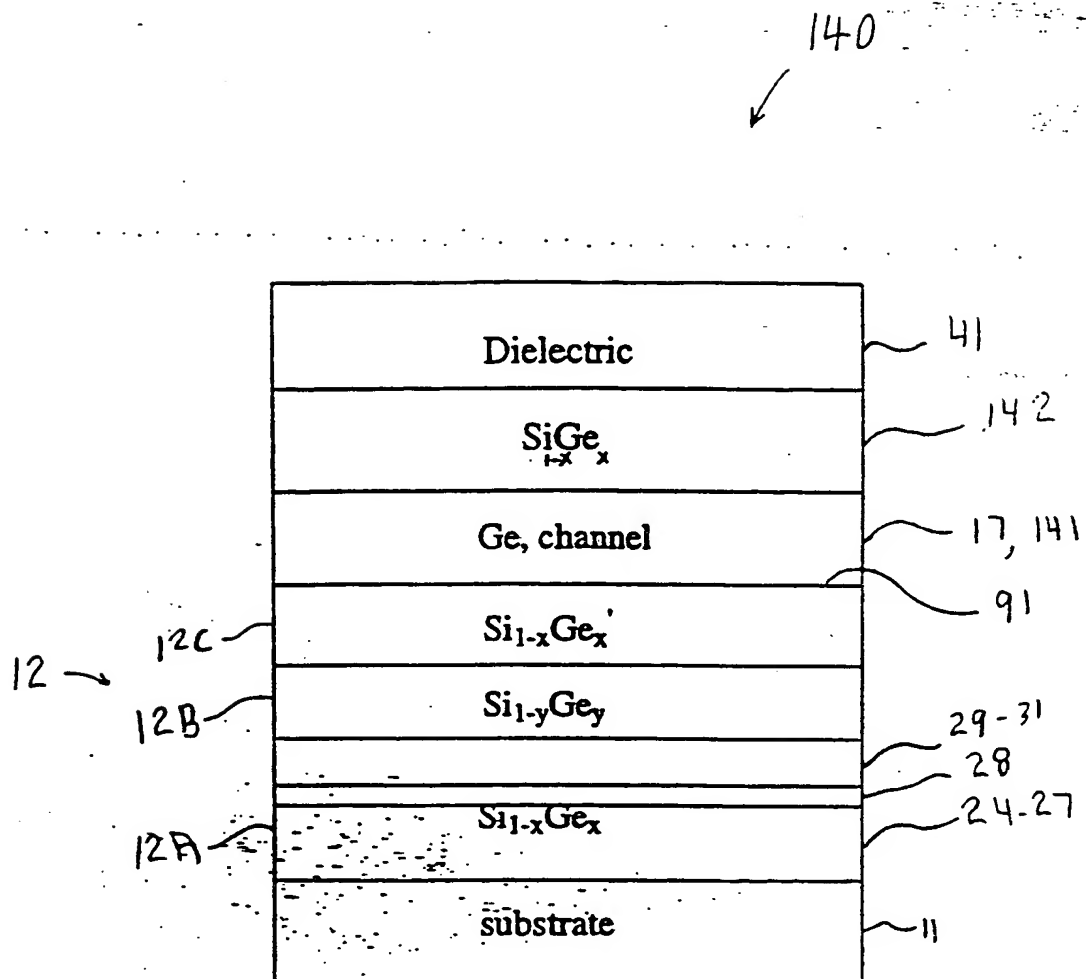


Fig 13

23 140

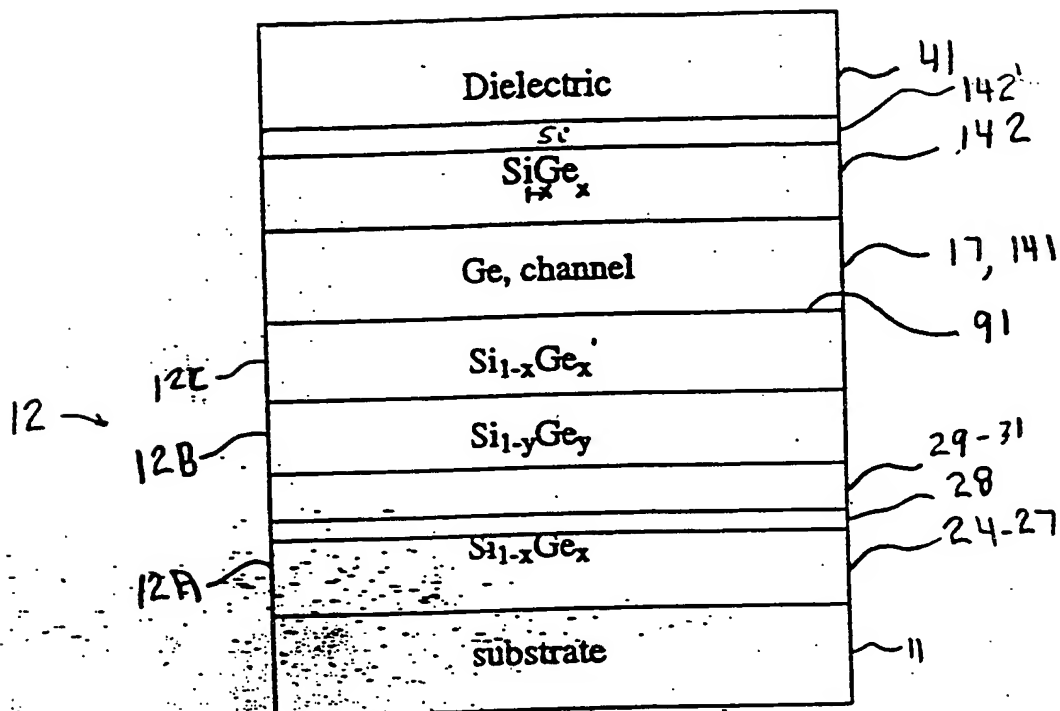


Fig 13A

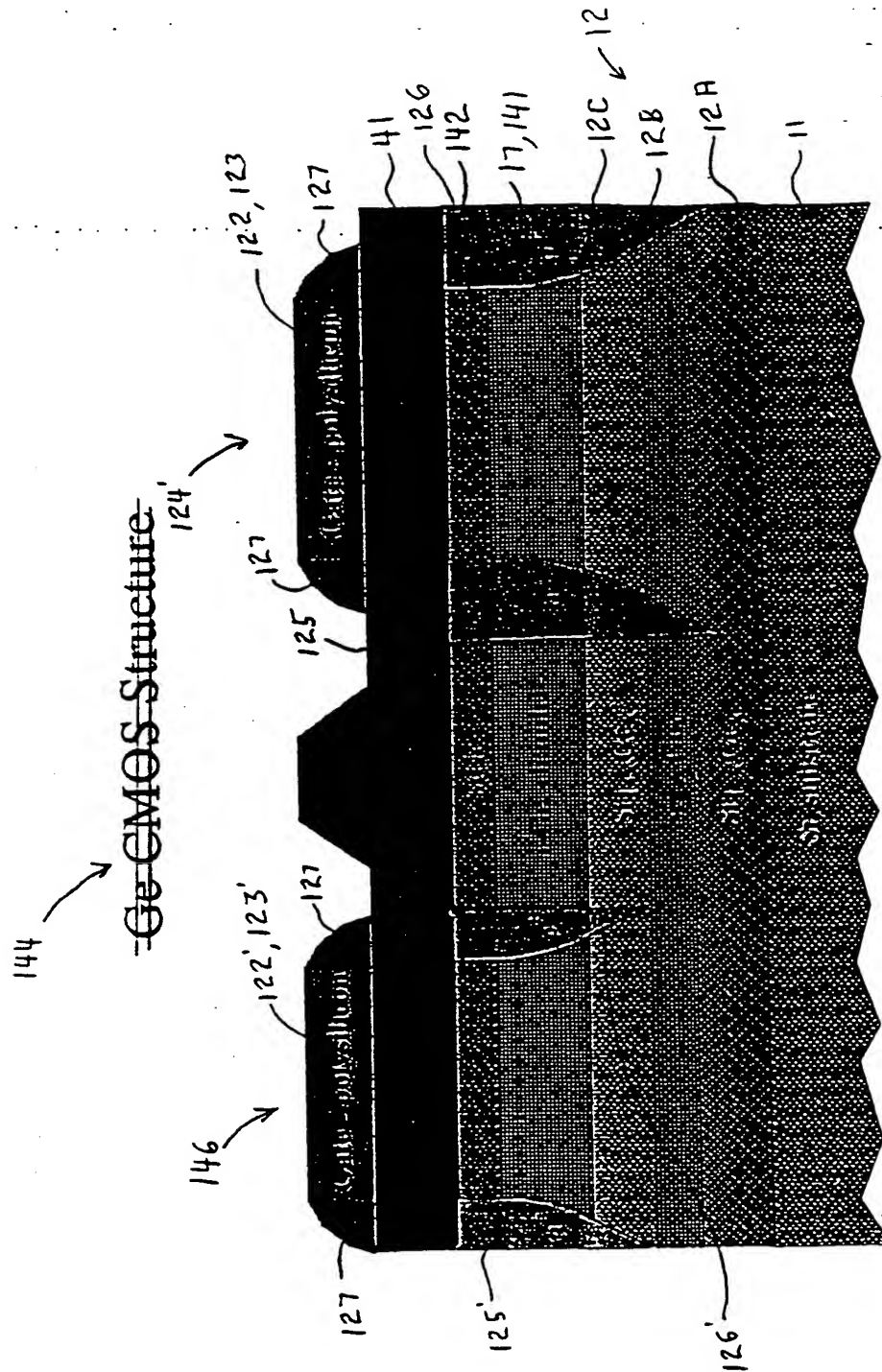


Fig 14

# ~~Ge Complementary FET Structure~~

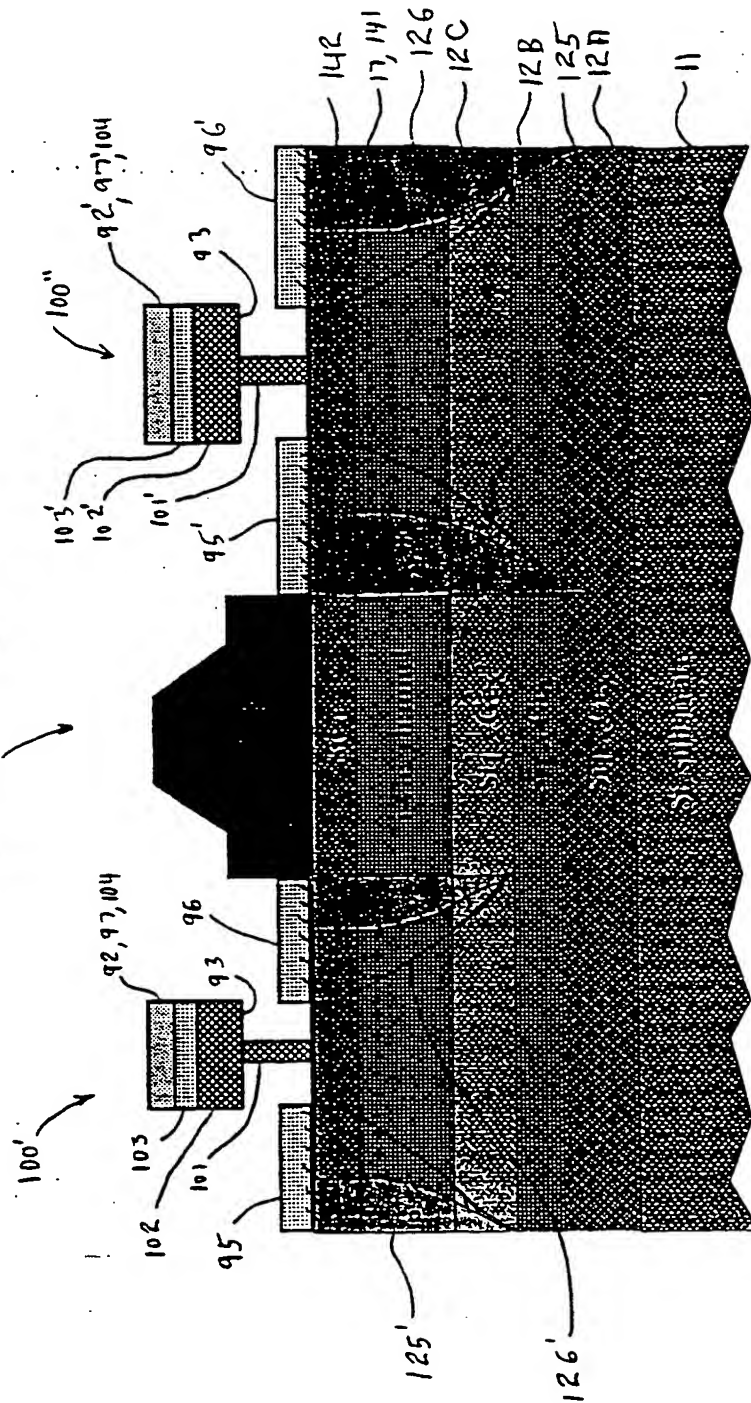


Fig 15

## INTERNATIONAL SEARCH REPORT

Initial Application No.

PCT/US 00/06258

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H01L29/778

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 241 197 A (MURAKAMI ET AL.) 31 August 1993 (1993-08-31) cited in the application  the whole document	1, 13, 26, 37, 52, 69, 89, 110, 118-126, 131-137
A	PATENT ABSTRACTS OF JAPAN vol. 017, no. 484 (E-1426), 2 September 1993 (1993-09-02) & JP 05 121450 A (HITACHI LTD), 18 May 1993 (1993-05-18)  abstract	1, 13, 26, 37, 52, 69, 89, 99, 110, 126, 131-137

☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

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## INTERNATIONAL SEARCH REPORT

International Application No.

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## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No. 1
A	G. HÖCK ET AL.: "High performance 0.25µm p-type Ge/SiGe MODFETs" ELECTRONICS LETTERS, vol. 34, no. 19, 17 September 1998 (1998-09-17), pages 1888-1889, XP000922999 cited in the application the whole document	1, 13, 26, 37, 52, 69, 89, 99, 110, 126, 131-137
A	KONIG U ET AL: "P-TYPE GE-CHANNEL MODFET'S WITH HIGH TRANSCONDUCTANCE GROWN ON SI SUBSTRATES" IEEE ELECTRON DEVICE LETTERS, US, IEEE INC. NEW YORK, vol. 14, no. 4, 1 April 1993 (1993-04-01), pages 205-207, XP000426251 ISSN: 0741-3106 cited in the application the whole document	1, 13, 26, 37, 52, 69, 89, 99, 110, 118-126, 131-137
A	MILIND GOKHALE ET AL: "ENHANCED PERFORMANCE OF PMOS AND CMOS CIRCUITS USING SELF-ALIGNED MOSFETS WITH MODULATION DOPED SI-GE CHANNEL" PROCEEDINGS OF THE BIENNIAL UNIVERSITY / GOVERNMENT / INDUSTRY MICROELECTRONICS SYMPOSIUM, US, NEW YORK, IEEE, vol. SYMP. 10, 1993, pages 219-222, XP000410475 the whole document	1, 13, 26, 37, 52, 69, 89, 99, 110, 118-126, 131-137
A	KONIG U ET AL: "SiGe HBTs and HFETs" SOLID STATE ELECTRONICS, GB, ELSEVIER SCIENCE PUBLISHERS, BARKING, vol. 38, no. 9, 1 September 1995 (1995-09-01), pages 1595-1602, XP004062484 ISSN: 0038-1101 the whole document	1, 13, 26, 37, 52, 69, 89, 99, 110, 126, 131-137

# INTERNATIONAL SEARCH REPORT

Inter. Patent Application No.  
PCT/US 00/06258

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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JP 05121450 A	18-05-1993	NONE	

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